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Bulletin of the Society of Economic Geologists

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ECONOMIC GEOLOGY

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ZONAL MINERALIZATION AND SILICIFICATION IN THE HORSESHOE AND SACRAMENTO DISTRICTS, COLORADO.[1]

ROBERT D. BUTLER AND QUENTIN D. SINGEWALD.

ABSTRACT.

The Horseshoe and Sacramento districts lie near the Alma and Leadville districts, Colorado. Paleozoic sedimentary rocks intruded by Tertiary (?) porphyry sills are folded into a northwestward trending asymmetrical anticline, whose steep west limb is broken by the London reverse fault, with an apparent vertical displacement of around 3,000 feet.

All the known ores, which form small silver-lead replacement deposits along small fissures in pre-Pennsylvanian dolomites, occur on the east or hangingwall side of the London fault. These favorable stratigraphic horizons, which lie just below those that contain the valuable gold-quartz veins on the footwall side of the London fault in the nearby London mine, lie far below the surface west of the fault in the Horseshoe and Sacramento districts.

Mineralization includes widespread recrystallization of the dolomites, less widespread replacement of dolomite by jasperoid, and deposition of ore accompanied by additional local wall rock alteration. Field and, particularly, microscopic observations dealing with all these processes are discussed.

The ores mainly contain pyrite, sphalerite, galena, tennantite, and argentite in a gangue of quartz, barite, carbonate, and recrystallized and silicified country rock; manganiferous ankerite, luzonite, chalcopyrite, and an unidentified sulphide locally occur in small amounts. These minerals exhibit a zonal distribution as to mineral species, textures, and compositional variations. Following the precedent established for the Leadville region, non-baritic ores in the central zone of ore deposition may be classed as "intermediate mesothermal," baritic ores more distant as "cooler mesothermal," and the most distant as "telethermal." The pro-

[1] Published by permission of the Director of the Geological Survey, United States Department of the Interior.

ductive area is confined to the "intermediate" and the inner portion of the "cooler mesothermal" zones.

The jasperoids are grouped into three textural types: (*1a*) anhedral-nodular, (*1b*) anhedral-granular, and (*2*) euhedral. Particularly significant is their zonal arrangement, which reveals the finest-grained textures nearest the center of ore deposition.

Economic interest pertains not only to discovery of new orebodies within the area of known mineralization but also to the possibilities at depth in favorable horizons west of the London fault. The question of possible southward continuation of the London gold-quartz veins from the Alma district is highly important but no significant data pertaining to it have been obtained.

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INTRODUCTION.

ORE has been mined from deposits on both sides of the London fault. In the Horseshoe and Sacramento districts lead-silver replacement ores east of the fault were mined from 1870 to 1900, but since that time desultory prospecting has been the only activity. The estimated value of the mineral production, $300,000, is attributed to three principal mines as follows: Sacramento, $200,000; Mudsill, $60,000; and Sherwood, $40,000. In the Alma district, the gold-quartz veins of the London group of mines on the west side of the London fault have produced more than 20 million dollars and are still being mined.

The regional geologic structure is such that rocks and structural features favorable to the emplacement of the gold-quartz ores of the Alma district are present at considerable depth below the surface in the Horseshoe and Sacramento districts, whereas the rocks and structural features that contain the lead-silver ores of the Horseshoe and Sacramento districts have been eroded from the area immediately east of the London fault in the Alma district.

The studies described in this paper were undertaken for the purpose of outlining favorable prospecting areas on the east side of the fault in the Horseshoe and Sacramento districts and to ascertain possible relations between gold-quartz ores west of the London fault and replacement silver-lead ores east of the fault.

Location and Topography.—The Horseshoe and Sacramento districts in Park County, central Colorado, lie south of the Alma district and east and southeast of the Leadville district (Fig. 1). The Horseshoe district coincides with the drainage area of Fourmile Creek; the Sacramento district includes the drainage area of Big and Little Sacramento Creeks. This paper is principally concerned with the portions of these districts between Pennsylvania Mountain and Brown's Pass that are on the east side of the London fault.

The broad upland basin of South Park forms the eastern, and the Mosquito or Park Range forms the western boundaries of the districts. The greater part of the area adjacent to the fault ranges from 11,000 to 13,000 feet in altitude. The streams flow

in glaciated gulches with walls from one to three thousand feet in height. Divides between the gulches are broad and their gentle slope is an expression of the regional easterly dip of the sedimentary rocks.

Previous Geologic Work.—In the course of his work on the

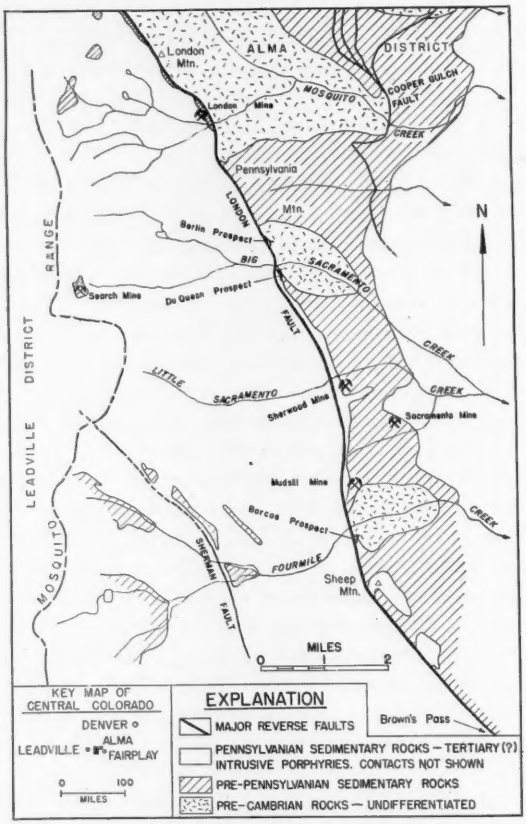

FIG. 1. Generalized geologic map of the Horseshoe and Sacramento districts and the southern part of the Alma district. Insert—Key map of central Colorado.

Leadville mining district, S. F. Emmons [2] studied this area as well as the Alma district. More recently, Behre [3] and Loughlin and Behre [4] have described deposits located near the crest of the Mosquito Range which in part are geographically within the Horseshoe district but geologically belong to the Leadville district. A series of papers has been pubished on the Alma district,[5] and one contains a general description of the structural features found along the London fault zone.[6] A more complete publication is in press.[7]

Field Work and Acknowledgments.—Q. D. Singewald was in charge of field work done during the summer of 1935. The specimens were studied in the laboratory by R. D. Butler, who assumes responsibility for the microscopic descriptions.

The writers are indebted to Dr. W. H. Newhouse for aid and discussion during the course of the laboratory work; to Dr.

[2] Emmons, S. F.: Geology and mining industry of Leadville, Colorado. U. S. Geol. Surv. Mon. XII: 135–169, 1886.

[3] Behre, C. H., Jr.: Revision of structure and stratigraphy in the Mosquito Range and the Leadville district, Colorado. Colo. Sci. Soc. Proc., 12: 37–57, 1929–1931. Preliminary geological report on the west slope of the Mosquito Range in the vicinity of Leadville, Colorado. Colo. Sci. Soc. Proc., 14: 49–79, 1939.

[4] Loughlin, G. F. and Behre, C. H., Jr.: Zoning of ore deposits, Leadville district, Colorado. Econ. Geol., 29: 215–254, 1934.

[5] Singewald, Q. D. and Butler, B. S.: Preliminary geologic map of the Alma mining district, Colorado. Colo. Sci. Soc. Proc., 12: 295–308, 1929–31. Singewald, Q. D. and Butler, B. S.: Preliminary report on the geology of Mount Lincoln and the Russia mine, Park County, Colorado. Colo. Sci. Soc. Proc., 12: 389–406, 1929–31. Singewald, Q. D. and Butler, B. S.: Suggestions for prospecting in the Alma district, Colorado. Colo. Sci. Soc. Proc., 13: 89–131, 1933. Singewald, Q. D.: Alteration as an end phase of igneous intrusion in sills on Loveland Mountain, Park County, Colorado. Jour. Geol., 40: 16–29, 1932. Singewald, Q. D.: Igneous history of the Buckskin Gulch stock, Colorado. Am. Jour. Sci., 24: 52–67, 1932. Singewald, Q. D.: Alma district. XVI Int. Geol. Cong. Guidebook 19: 107–111, 1932. Singewald, Q. D.: Relations of hydrothermal alteration of porphyries to ore deposition in the Alma district, Colorado. Econ. Geol., 30: 518–539, 1935. Loughlin, G. F. et al.: Zoning in certain mining districts in the Mosquito and San Juan Mountains, Colorado. XVI Int. Geol. Cong. Rept., 1: 433–442, 1936. Johnson, J. H.: Paleozoic formations of the Mosquito Range, Colorado. U. S. Geol. Surv. Prof. Pap. 185–B, 1934.

[6] Singewald, Q. D. and Butler, B. S.: Structure and mineralization along the London fault, Colorado. A. I. M. E. Trans., 126: 426–441, 1937.

[7] Singewald, Q. D. and Butler, B. S.: U. S. Geol. Surv. Bull. 911 (in press).

Waldemar Lindgren for helpful comment on microscopic relations; to Dr. L. B. Riley who accompanied Butler on revisits to several of the old mines during 1937; to Mr. C. L. Roloson for drafting aid; and to Dr. Eugene Callaghan and Dr. D. M. Fraser for reading and commenting upon the manuscript.

GENERAL GEOLOGY.

Pre-Cambrian Rocks.

The pre-Cambrian rocks[8] consist of schist, pegmatite, and granite named in order of abundance. The schist is a quartz-mica variety, containing many narrow lit-par-lit pegmatite injections. The regional strike of the foliation is northeast; dips are steep or vertical. Granite of the " corn rock " type has been noted in several small outcrops on the north side of Big Sacramento Gulch, where it invades the injected schist.

The areal distribution of pre-Cambrian rocks, undifferentiated, is shown in Fig. 1. These rocks crop out east of the London fault in relatively small areas in the gulches.

Paleozoic Sedimentary Rocks.

General Features. Two broad divisions of the Paleozoic sedimentary rocks are possible: (1) the pre-Pennsylvanian strata, composed of dolomites, quartzites, and shales with various transitional facies; and (2) the Pennsylvanian strata, composed of arkosic and micaceous sandstones, conglomerates, thin carbonaceous limestones and shales, and quartzites. The basal quartzite of the pre-Pennsylvanian sedimentary rocks lies unconformably upon a peneplaned surface of pre-Cambrian crystalline rocks.

Pre-Pennsylvanian Rocks.—The pre-Pennsylvanian sedimentary rocks range in age from Cambrian to Mississippian, Silurian excepted. The thicknesses of the separate units vary throughout the region. A stratigraphic column, measured on both sides of Fourmile Creek is listed in Table I. For further information the

[8] Lovering, T. S.: Geologic history of the Front Range, Colorado. Colo. Sci. Soc. Proc., 12: 61–74, 1929–1931.

reader is referred to Johnson's work [9] or to one of the later publications on Alma or Leadville.

TABLE I.

COMPOSITE STRATIGRAPHIC COLUMN, FOURMILE GULCH, HORSESHOE DISTRICT, COLORADO.

Age.	Name of Adopted Unit.		Thickness, Feet.	Description.	Miners' Term.
Pennsylvanian	Weber (?) formation		2500+	Interbedded quartzite, conglomerate, grit, arkose, shale, and some limestone, nearly all micaceous. Some shale highly carbonaceous. Shale predominates near base, arenaceous beds in upper part. Thickness not measured.	Weber grits
	Hiatus				
Mississippian	Leadville dolomite		112	Blue to black, mostly dense-textured, massive-bedded dolomite; "zebra rock," chert, and limestone-breccia are common. Basal 15 feet is quartzite zone, composed of quartzite, sandstone, and limestone breccia. Variable and lenticular.	Blue lime
	Hiatus				
Upper Devonian	Chaffee formation	Dyer dolomite member	107	Fairly thin-bedded, mostly dense, white and blue dolomite. Exposed surfaces generally smooth. Dark-blue massive bed characteristic of uppermost part.	
		Parting quartzite member	60–75	Cross-bedded and conglomeratic quartzite and sandy limestone. Quartz pebbles subangular. Locally, slightly shaly.	Parting quartzite
	Hiatus				
Lower Ordovician	Manitou limestone		130	Thin-bedded white and medium blue, mostly "crystalline" dolomitic limestone. Weathers light gray, developing siliceous ribbing. Locally, slightly shaly at top.	White lime
Upper Cambrian	Sawatch quartzite	Peerless shale member	50	Thin-bedded shales, dolomitic limestones, and sandy limestones. Limestone weathers brown, shale green. Numerous shale partings.	Transition shales
			60	Fairly thick-bedded, white, fine-grained quartzite. A few beds have small quantities of carbonate cement. At base is a white quartzite conglomerate with pebbles less than 1" in diameter.	Lower quartzite
	Unconformity				
Pre-Cambrian				Schist, granite, and pegmatite.	

The Dyer and Leadville dolomites, which together constitute the "Blue limestone" of popular nomenclature, contain the lead-silver orebodies of the districts. As the Leadville dolomite is the host rock to more ore than the Dyer, distinction between the two is of prime importance. The Leadville is generally darker colored than the Dyer, has patches of "zebra rock" or white recrystal-

[9] Johnson, J. H.: *op. cit.*, pp. 17–19.

lized dolomite, contains more chert nodules, is more massively bedded, and weathers to rougher surfaces.

Under the microscope both the Leadville and the Dyer dolomites consist of the same minerals and show the same textural variations. Recrystallization has affected both, apparently independent of areal position with respect to orebodies. In places, recrystallization of the Leadville dolomite has produced irregular subparallel bands of white dolomite, whose widths average one-eighth inch. The alternation of these white bands with the dark bluish gray dolomite is responsible for the designation "zebra rock."[10] (Fig. 9).

It has been shown[11] that insoluble residues from the Leadville dolomite in general are darker and smaller in quantity than those from the Dyer dolomite. In the London mine, however, Riley found that the amounts of insoluble residues from the Leadville range between such wide limits that it is doubtful if this criterion alone will prove sufficient to identify the formation near the London orebodies.[12]

The basal part of the Leadville dolomite consists of an impure, sandy zone, similar to the one near Leadville described by Behre.[13] This key horizon ranges to a maximum thickness of 15 feet. Although termed "quartzite," in places it is little more than a sandy dolomite (Table II). In an excellent exposure about one-half mile east of the Mudsill mine, sandstone predominates; here the quartz grains are set free by the weathering of a carbonate matrix.

The distribution of pre-Pennsylvanian strata is indicated in Fig. 1. The Dyer and Leadville dolomites are exposed over considerable areas east of the London fault on both limbs of the faulted

[10] Emmons, S. F., Irving, J. D. and Loughlin, G. F.: Geology and ore deposits of the Leadville mining district, Colorado. U. S. Geol. Surv. Prof. Pap. 148: 33, 1927.

[11] Singewald, Q. D. and Reed, C. M.: Insoluble residues from Paleozoic limestones of the Mosquito Range, Colorado. Jour. Sed. Petrology, 5: 115–122, 1935.

[12] Riley, L. B.: Oral communication, Aug. 1937.

[13] Behre, C. H., Jr.: Revision of structure and stratigraphy in the Mosquito Range and the Leadville district, Colorado. Colo. Sci. Soc. Proc., 12: 38–41, 1929–1931.

TABLE II.

SECTION OF BASAL QUARTZITE MEMBER OF THE LEADVILLE DOLOMITE, NORTH SIDE OF FOURMILE GULCH.

Age.	Lithologic Zone.	Thickness, Feet.	Description.
			Heavy-bedded, dark blue-gray dolomite with "zebra" recrystallization structure (Leadville dolomite).
		3	Dark gray dolomite beds, 6–8 inches thick, each grading towards sandstone at top and each capped with 1 inch of brown-weathering sandstone.
		3	Heavy-bedded, dark gray dolomite.
Mississippian	Quartzite Zone	3	Dolomite breccia with sandy cement, and intercalated sandstone. Weathers light brown. This is principal arenaceous stratum.
		5	Massive dolomite with a few thin beds of brown-weathering sandstone. Sandstone beds lenticular.
		1	Basal sandstone. Grain sizes not appreciably greater than in other sandstones in the member.
	—Hiatus—		
Devonian			Massive dark blue dolomite with irregular veinlets of white carbonate. Typical of upper part of Dyer dolomite in this area.

anticline. West of the fault, these beds are buried at considerable depth in the trough of the down-faulted syncline, but reappear at the surface near the crest of the range.

Pennsylvanian Rocks.—The youngest sedimentary rocks are those of the Weber (?) formation, which rests upon the eroded surface of the Leadville dolomite. The basal bed in most places is a thin shale, but locally is limestone breccia or quartzite; the total thickness is about 2,500 feet, although it cannot be measured accurately since the overlying formations have been eroded. The lowermost several hundred feet is predominantly shaly; the remainder is dominantly sandy. Impure facies and cross-bedding are abundant. Individual horizons are lenticular over short distances, definite correlations within the area are impossible, and

except in a general way, the position of an outcrop within the section cannot be ascertained. For these reasons, the structure west of the London fault where Weber (?) strata outcrop, is imperfectly known. Detailed sections of the Weber (?) formation have been compiled by Johnson.[14]

Tertiary (?) Intrusive Rocks.

Tertiary (?) intrusive porphyries of the type characteristic of the central Colorado mineral belt are abundant. In the Alma district their compositions range from monzonitic diorite to salic quartz monzonite.[15] The porphyries along the London fault zone in the Horseshoe and Sacramento districts are either southward extensions of masses that crop out in the Alma district, or if not visibly connected, are megascopically identical. Following the precedent established for similar rocks in the Leadville district, Gray and White porphyry groups, both of which are sub-divisible into several facies, are recognized. Gray porphyry predominates in the Sacramento district, White porphyry in the Horseshoe, yet both are found in each district. No orebodies with porphyry wall rocks have been found in the Horseshoe or Sacramento districts.

The porphyries occur chiefly in the form of sills. The most favored stratigraphic position is from one-half foot to five feet above the top of the Leadville dolomite, where not only is one or both of the porphyries invariably present but also the sills may attain great thickness. For example, at the heads of Big and Little Sacramento Gulches there are two sills, separated by a few feet of Weber (?) strata, with an aggregate thickness of about 2,000 feet. Although thick sills are rare at other stratigraphic horizons, sills less than a hundred feet in thickness are common in the Cambrian quartzites and in the Weber (?) formation, and they have been observed also in the limestones. As in the London

[14] Johnson, J. H.: Paleozoic formations of the Mosquito Range, Colorado. U. S. Geol. Surv. Prof. Pap. 185–B: 28–43, 1934.

[15] Singewald, Q. D.: Alteration as an end phase of igneous intrusion in sills on Loveland Mountain, Park County, Colorado. Jour. Geol., 40: 16–29, 1932. Igneous history of the Buckskin Gulch stock, Colorado. Am. Jour. Sci., 24: 52–67, 1932. Relations of hydrothermal alteration of porphyries to ore deposition in the Alma district, Colorado. ECON. GEOL., 30: 518–539, 1935.

mine,[16] intricate interfingering of White and Gray porphyries with each other and with Weber (?) strata occurs only in the immediate zone of the London fault. Narrow inconspicuous porphyry dikes are present in pre-Cambrian rocks and a few large "feeder" dikes cut the sedimentary series.

Quaternary Deposits.

Quaternary deposits comprise glacial debris, fluvial gravels, and talus.

Structure.

Regional Features.—The area lies on the eastern flank of the broad Sawatch uplift, and the rocks have a homoclinal easterly dip of about 15°. A northwest-trending, asymmetric anticline crosses the area. The steeper southwest limb has been broken by the London fault and the combined vertical displacement of folding and faulting is about 3,000 feet. Two other conspicuous but lesser faults, the Cooper Gulch and the Sherman, are present in the area. Minor faults, some of which are mineralized or have replacement orebodies adjacent to them, are abundant.

Major Folds and Faults.—The London fault and anticline has been mapped for a distance of 8 miles within the Horseshoe and Sacramento districts. It continues northwest through the Alma district, crosses the crest of the Mosquito Range and joins the Mosquito fault near Climax. It also continues southeastward, but it has not been mapped in detail beyond Brown's Pass.

The fold and fault form a relatively narrow broken zone. The axes of the anticline and of the syncline to the west average 0.3 mile apart. The fault lies between the axes but its distance from them is variable, for the strike of the fault is only locally parallel to the axes. Beds adjacent to the fault on each side are steep or, in places, overturned, perhaps in part owing to drag.

Intersection of the homoclinal east-dipping beds with the northwest-trending London fault results on the whole in the cropping out of higher stratigraphic horizons on both sides of the fault in

[16] Singewald, Q. D. and Butler, B. S.: Suggestions for prospecting in the Alma district, Colorado. Colo. Sci. Soc. Proc., 13: 89–131, 1933.

the Horseshoe and Sacramento districts than in the Alma district, although reversals of the regional southeasterly plunge of the anticlinal and synclinal axes occur locally. On Sheep Mountain, the lower Paleozoic rocks and the basal beds of the Weber (?) formation are exposed on the east side of the fault and middle or upper Weber (?) beds on the west side, whereas on London Mountain, pre-Cambrian formations crop out on the east and the Leadville and lower Weber (?) strata on the west side.

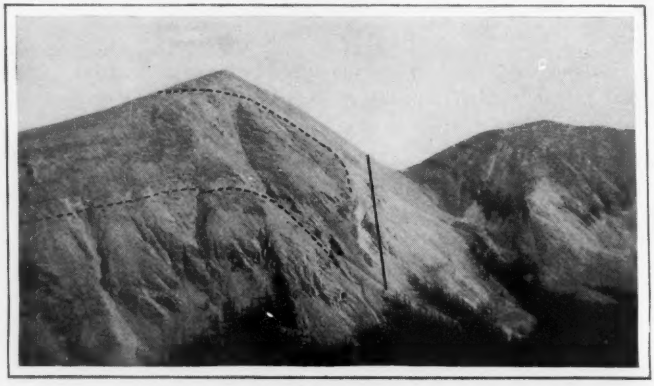

FIG. 2. Sheep Mountain looking south across Fourmile Gulch from the Mudsill mine. Lamb Mountain on the right. Solid line—trace of London fault on the surface. Upper dotted line—Pennsylvanian-Mississippian contact. Lower dotted line—Cambrian-pre-Cambrian contact. Width of area in view, one mile.

Recognizable outcrops of the London fault itself are few. Where visible, the east dip of the fault plane ranges between 60° and vertical. It may be less than 60° in places, however, as a major fault dipping 50° to the east, which may be the London, has been cut by the Barcoe Tunnel on Sheep Mountain.[17] The general aspect of the anticlinal structure east of the fault is shown in Fig. 2. Fig. 3 illustrates a generalized section through the fault at the Mudsill mine.

[17] Butler, B. S.: Oral communication, July, 1937.

The Cooper Gulch fault, which shows maximum displacement on Loveland Mountain in the Alma district, cannot be traced south of Pennsylvania Mountain. This fault is associated with a sharply overturned anticline, dips about 30° eastward, and has a maximum stratigraphic displacement of 450 feet. The Sherman fault, in the western part of the area, is poorly exposed. It has had less movement along it than the London, but is associated with overturned beds.

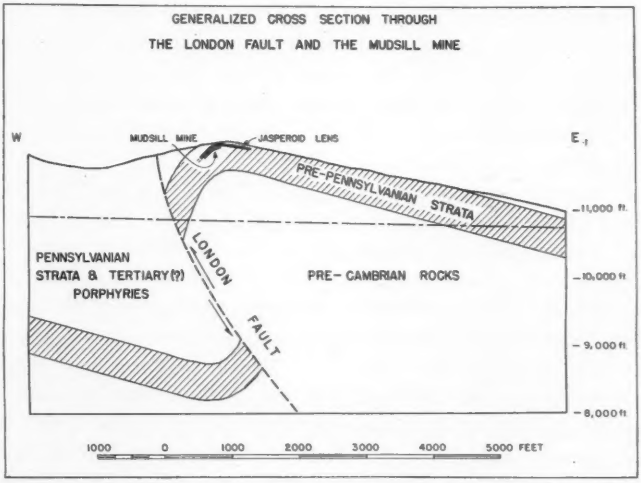

FIG. 3. Generalized cross-section showing the structure in the vicinity of the Mudsill mine. The broken line is the profile of Fourmile Creek projected on the plane of the section.

Minor Faults and Fissures.—Minor faults and fissures in great numbers accompany the London fault. In the Horseshoe and Sacramento districts only those on the east or hangingwall side are well displayed, whereas in the Alma district the workings of the London mine reveal those in the footwall. The auxiliary fractures in the hangingwall can be broadly divided into divergent, parallel, and transverse types.

The divergent fissures are most numerous. They strike in a north to northeast direction, diverging northward from the London fault at angles between 15 and 40 degrees, and they dip in either direction at moderate to steep angles. Although most of the orebodies are along or adjacent to these fissures, many unmineralized fissures belong to this group. Displacements on the fractures range from almost zero to one hundred feet although more than fifty feet is uncommon. The movement on most is similar to that on the London fault; *i.e.*, the east wall was displaced upward relative to the west wall. A few faults and mineralized fissures diverge southeastward in the hangingwall of the London fault.

Parallel faults strike and dip approximately parallel to the London fault, lie within 300 feet of it, and have had similar relative movement.

Transverse faults trend east or northeast. It is probable that nearly all displace the London fault and are not confined to one wall, as are most of the divergent faults. Transverse faults are well-exposed in the London mine but are difficult to recognize on the surface. Several are inferred on the north side of Pennsylvania Mountain, and elsewhere apparent displacements of the London fault suggest their presence.[18] Near the Sherwood mine, irregularities on the anticlinal limb east of the fault could be explained by transverse displacement but the quality of rock exposures is so poor that no definite trend could be established.

Minor faults not directly associated with the London fault occur both east of the anticline and west of the syncline. Some, although not all, are mineralized.

Contrast Between Faulting and Rock Brecciation.—From the above discussion it should be realized that, in addition to folding, the megascopic effects of deformation in the vicinity of the London fault are a main shear zone; a belt of auxiliary faults and fractures whose numbers and intensities decrease progressively away from the main shear; and comparatively few faults in outlying areas beyond the anticlinal and synclinal axes. The micro-

[18] Singewald, Q. D. and Butler, B. S.: Structure and mineralization along the London fault, Colorado. A. I. M. E. Trans., 126: 436, 1937.

scopic effects, as shown by brecciation phenomena, reveal, on the contrary, no such gradation.

The dolomites in general show more brecciation than other rocks and it is nearly impossible to obtain a cubic inch of either the Leadville or Dyer dolomites that has not been affected. Veinlets of white carbonate have filled most of the cracks. Although outcrops of Leadville dolomite in general are more shattered than those of Dyer, microscopic evidence does not indicate more brecciation in the Leadville.

Age of Intrusion and Deformation.

Regional studies have led to correlation of much of the Laramide igneous activity in the Alma-Leadville region with deposition of the Denver formation (the late Upper Cretaceous and Eocene (?)).[19] The intrusive porphyries were involved in the major deformation of the Laramide orogeny. Along the London fault, moreover, complex interfingering of porphyries suggests that slight deformation accompanied or preceded intrusion, because elsewhere the intrusive structures are not complex. Irregular displacements of contacts of porphyry sills along certain faults in the Alma district have been explained as a result of pre-intrusive faulting.[20]

Following intrusive activity, the Laramide orogeny produced the major folds and reverse faults as well as the accompanying minor faults and brecciation. The auxiliary breaks doubtless had their inception as the major folds were developing but most of the movement along them took place after the folds were broken by faulting.

Mineralization was later than the major structural development, but was accompanied and followed by the minor amounts of deformation exhibited by brecciated hypogene minerals. Throughout the area, post-mineral movements occurred, principally along earlier-formed faults, but little information is available because of the paucity of exposed orebodies.

[19] Lovering, T. S. and Goddard, E. N.: Laramide igneous sequence and differentiation in the Front Range, Colorado. Geol. Soc. Amer. Bull., 49: 41–45, 1938.

[20] Singewald, Q. D. and Butler, B. S.: Preliminary geology map of the Alma mining district, Colorado. Colo. Sci. Soc. Proc., 12: 306, 1929–1931.

ORE DEPOSITS.

General Character.

The deposits in the area are small replacement bodies of silver-lead ores contained in either the Leadville or Dyer dolomites. Although most of the workings are inaccessible, mineralized fissures were observed adjacent to some replacement ores. Of the three principal producers, the Sherwood and Mudsill mines are located on the steep western limb of the London anticline, close to the fault, whereas the Sacramento mine is in the area of regional eastward dip, 4,000 feet east of the London fault. The Sherwood and Sacramento ores lay close to the top of the Leadville dolomite, the Mudsill near the top of the Dyer.

Although production has been limited to the ground between Fourmile and Little Sacramento creeks, on the north flank of the Sheep Mountain anticlinal nose, innumerable abandoned pits and adits of small size testify to extensive prospecting elsewhere. Mineralization extends southward as far as Brown's Pass, but only one prospect showing ore minerals has been found north of Little Sacramento Creek.

Three ambitious prospecting ventures have proved disappointing. The inaccessible Du Queen or Majestic adit, driven south along the east wall of the London fault from the valley of Big Sacramento Creek in 1910, contains 1,200 feet of horizontal workings. No production was reported and no mineral matter was found on the dump. The Barcoe adit, recently driven south from Fourmile Gulch to explore the London fault zone west of Sheep Mountain, does not show promising indications. Work on it was abandoned in the fall of 1937 after it had attained a length of 2,800 feet. The Berlin adit, on the north side of Big Sacramento Gulch, was driven 534 feet N. 25° W. through the London fault, the east wall of which is 460 feet from the portal. Brecciated arkose of the Weber (?) formation is exposed at the face. There is no evidence of mineralization.

The ores are divisible into non-baritic and baritic facies. The non-baritic ores are found between Little Sacramento and Four-

mile creeks in a narrow zone immediately east of the London fault. This zone, apparently restricted to the western limb of the anticline, pinches southward, for it is at least 2,000 feet wide near the Sacramento mine but only a few hundred feet wide near the Mudsill mine. The baritic ores occur east of the belt of non-baritic ores and on Sheep Mountain.

Non-Baritic Ores.—The non-baritic ores, of which that on the dump of the Sherwood mine is the principal example, are composed of pyrite, sphalerite, galena, subordinate tennantite and argentite, minor amounts of chalcopyrite and an unidentified sulphide mineral in a gangue of quartz, manganiferous ankerite, ferruginous dolomite, dolomite, and silicified and recrystallized country-rock dolomite. Pyrite dominates, although brown sphalerite is nearly as abundant. Pyrite and quartz form coarse-grained intergrowths. In some specimens the mineral aggregate is a heavy, massive intergrowth of sulphides with either quartz or country rock; in others the minerals are disseminated in small masses and veinlets throughout the country rock. No ore was found at the Mudsill mine, so its classification is questionable, but barite, pyrite, sphalerite, galena, tennantite, luzonite, and chalcopyrite are found along an inconspicuous fissure 200 feet to the east. This is the only recognized occurrence of luzonite in the region.

Baritic Ores.—In the baritic facies, galena is the most abundant metallic mineral. Although much of the original sphalerite may have been destroyed by oxidation, it is, nevertheless, not so abundant as in the non-baritic ores; moreover, it is greenish brown. Pyrite is fine-grained and occurs only in relatively minor quantities. Tennantite and argentite also are less common than in non-baritic ores. Silicified and recrystallized dolomite rock and ferruginous dolomite gangue are present, but quartz is negligible and no manganiferous ankerite was noted. Barite appears in diverse quantities and textures. Some ores are intergrowths of coarse platy barite and galena in which the barite plates attain lengths of 4 cm. or more. In others barite is in plates disseminated through recrystallized or silicified country rock or in com-

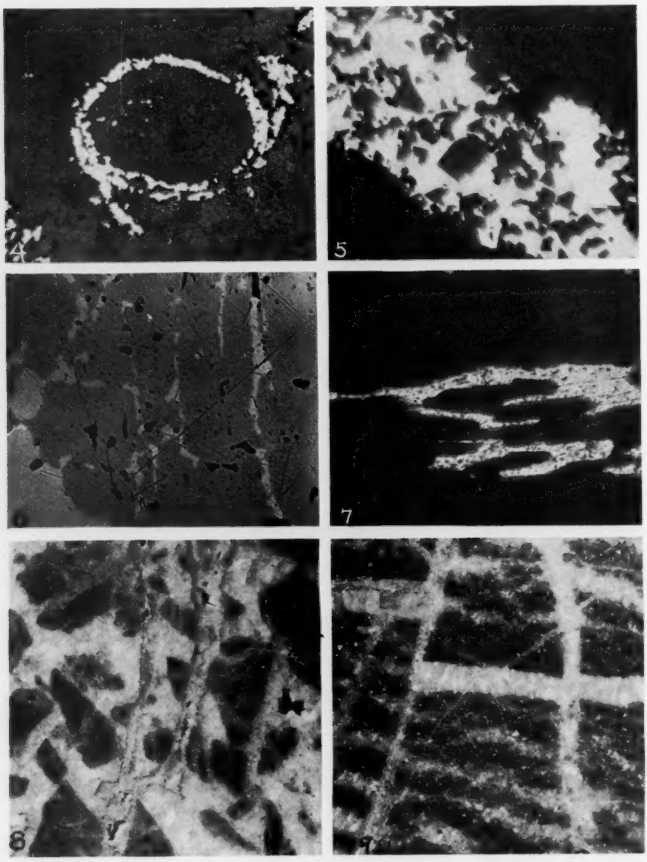

FIG. 4. Cross section of annular veinlet of pyrite (white) within Leadville dolomite. North of Mudsill mine. × 45.

FIG. 5. Replacement veinlet of galena (white) in Leadville dolomite. Sherwood mine. × 120.

FIG. 6. Intergrowth of tennantite (medium gray) and galena (light gray). Galena occurs in pseudo-veinlets. Black spots are pits on surface. Sherwood mine. × 120.

FIG. 7. Typical replacement of barite by vein quartz showing cor-

pact intergrowths of numerous platy crystals, 1 cm. in length, which have replaced country rock.

Oxidized Ores.—Oxidation has affected all of the deposits but in most of them, however, remnants of the hypogene minerals have been preserved. Secondary products include covellite, anglesite, hemimorphite, smithsonite, malachite, azurite, limonitic material, aragonite, and gypsum.

Mineralogy.

Metallic Minerals.—Pyrite grains in ore specimens range in average diameter from 1.0 cm. at the Sherwood mine to a fraction of a millimeter in the Sheep Mountain prospects, are euhedral except as modified by later replacement, are associated either with ore minerals or quartz, and in part show faint anomalous anisotropism under the microscope. Pyrite is veined and replaced by sphalerite but uncommonly by other sulphides. In the nonbaritic ores the periods of deposition of quartz and pyrite overlap. Late pyrite, forming tiny replacement veinlets in sphalerite, occurs only in the Sherwood ores. Pyrite forms massive intergrowths of tiny, anhedral grains, and irregular veinlets that have produced curious structures in the country rock dolomite (Fig. 4). It occurs in jasperoid, where its relations to pyrite in ores cannot, however, be ascertained.

Sphalerite is most abundant in the Sherwood ore although in other places much of it may have been removed by oxidation. It

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roded remnants of a single barite crystal (light gray) replaced by quartz (black). Sacramento mine, transmitted light. X-nicols. × 170.

FIG. 8. Epigenetic dolomite in the Leadville dolomite, showing three stages of deposition: (1) Brecciated Leadville dolomite (black) which contains recrystallized dolomite and epigenetic ferruginous dolomite (gray), (2) Epigenetic dolomite (white) cementing the black fragments, and (3) Veinlets of dolomite and ferruginous dolomite with vugs cutting white dolomite (2). Fourmile Gulch, incident light. × 2.5.

FIG. 9. Zebra rock facies of the Leadville dolomite. Sub-parallel bands of white dolomite from which impurities have been removed, alternate with dark blue impure dolomite. Later dolomite veinlets cut the banded structure. Little Sacramento Gulch, incident light. × 4.5.

ranges in color from a brown at the Sherwood mine to a deep resinous brownish green in the Sheep Mountain prospects. It contains no blebs of chalcopyrite as does sphalerite from the London mine. Sphalerite has replaced negligible amounts of pyrite and quartz, is considerably replaced by galena and tennantite, and is transected by tennantite and argentite veinlets and masses. It commonly forms irregular replacement masses and veinlets within brecciated dolomite country rock.

Galena is a conspicuous mineral in nearly all the mines and prospects, though it is relatively sparse near the southern edge of the area. It has irregularly replaced country rock, the early stages of replacement proceeding along boundaries of carbonate grains or along tiny veinlets that have selectively replaced carbonate grains (Fig. 5). Fractured barite along cleavage directions has also been widely replaced by galena. Where associated with other ore minerals, galena has irregularly replaced sphalerite, and is intergrown with tennantite and argentite.

Tennantite is widespread and moderately abundant between Little Sacramento and Fourmile creeks, but is virtually absent on Sheep Mountain. Microchemical tests on tennantite grains apparently free of argentite show silver. Most tennantite is associated with galena (Fig. 6). In some specimens galena-tennantite intergrowths could be described as pseudo-eutectic but these are localized and merge into less well-developed intergrowths. Some areas contain more galena than tennantite, others more tennantite. Stringers of galena appear as veinlets, but are presumably unreplaced remnants. In places tennantite appears to have formed earlier than galena, in others, later. A few galena-tennantite contacts follow cleavage directions of galena for a fraction of a millimeter; and in two or three places, straight-walled tennantite-argentite-chalcopyrite veinlets, 0.03 mm. wide, cut tiny masses of galena, and maintain the same width as where cutting sphalerite. Lindgren records that galena may be either earlier or later than tennantite with resulting development of pseudo-eutectic intergrowths by replacement.[21] Here for the most part tennantite formed after deposition of galena.

[21] Lindgren, W.: Pseudo-eutectic textures. ECON. GEOL., 25: 10, 1930.

Luzonite ($Cu_3(Sb, As)S_4$) [22] occurs with quartz, barite, and sulphides at a prospect near the Mudsill mine. Small irregular veinlets and masses of luzonite associated with tiny threads of oxidation (?) products are interlaced within tennantite. Hence, luzonite might be considered a supergene alteration product of tennantite, but, as tennantite at all other localities has altered to covellite, the luzonite here is probably hypogene.

Argentite in small amounts is fairly common north of Fourmile Creek, less common on Sheep Mountain, and apparently absent at the south edge of the area. In ores north of Fourmile Creek, argentite occurs in irregular masses within tennantite and in tiny cross-cutting veinlets, but in ores south of Fourmile Creek, it forms irregular, rounded, or lathlike blebs within galena. Deposition of argentite probably succeeded that of tennantite, but the evidence is not conclusive.

An insignificant amount of chalcopyrite is associated with tennantite in ores north of Fourmile Creek, but none was found in ores from Sheep Mountain. It is present in tiny masses, especially within tennantite veinlets.

In the Sherwood ores an unidentified sulphide mineral occurs in minute shredded intergrowths with argentite along narrow argentite-tennantite veinlets. The mineral is slightly darker and its polished surfaces are slightly harder than those of argentite. It is anisotropic in sky blue and purplish brown colors, whereas argentite shows yellow and violet anisotropism.

Gangue Minerals.—Distinction between gangue minerals and altered wall rock in districts containing replacement ores in calcareous rocks becomes a matter of personal opinion. In this paper, barite, quartz, and epigenetic carbonates are considered as gangue minerals, whereas recrystallized dolomite and jasperoid are considered products of wall-rock alteration, but demarcation is not everywhere possible. Moreover, much epigenetic carbonate may be derived from country rock.[23]

Barite is the most conspicuous gangue mineral throughout most

[22] Harcourt, G. A.: The distinction between enargite and famatinite (luzonite). Amer. Min., *22*: 517–525, 1937.

[23] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, pp. 252–253.

of the area, but is absent in a zone along the London fault between Little Sacramento and Fourmile creeks (Fig. 27). Near Big Sacramento Creek, barite occurs in one prospect, together with the only sulphides found north of Little Sacramento Creek.

Ores from the Sacramento mine are typical of the baritic facies. Individual crystals and bladed aggregates of barite show diversity in size. Barite has widely replaced country-rock dolomite, but has been replaced by quartz, carbonates, and galena. Its replacement by quartz is shown in Fig. 7. Its color is milky white except on Sheep Mountain where a glassy variety projects into fissures and cavities in jasperoids. Relation of barite to the various facies of silicified country rock is discussed on a later page.

Quartz is found as vein quartz, as crystals in vugs, and as jasperoid. The earliest generation of vein quartz occurs in minor quantities within or immediately adjacent to the London fault. It has been brecciated and replaced by fine-grained silica or jasperoid.

Appreciable amounts of vein quartz occur only in the productive area between Fourmile and Little Sacramento creeks. There, the quartz is coarse-grained, shows strain effects, and contains dusty inclusions. It replaces country rock and barite, and forms masses that have veined and replaced recrystallized dolomite, but in turn, it is cut by later carbonates. Coarse intergrowths of quartz with pyrite are common in the Sherwood ores.

Small, terminated quartz crystals, in most places associated with calcite and gypsum, have formed in vugs and narrow open fissures.

In addition to aragonite, six kinds of carbonates, including dolomite in original country rock, three varieties of gangue dolomite, and calcite in vugs, have been recognized. Descriptive features of these minerals are listed in Table III. Numbers 3, 4, and 5 in this table are included as gangue minerals.

Slightly manganiferous ankerite (3) occurs in isolated pink grains, 1.0 to 5.0 mm. in diameter, within recrystallized dolomite in a few specimens from the Sherwood mine. Tests to determine its composition, however, were not conclusive. Microchemical indications of manganese and iron were obtained, but the iron was

TABLE III.

OCCURRENCES AND CHARACTERISTICS OF CARBONATE MINERALS.

Descriptive Term.	Composition.	Refractive Index, ω.	Habit.	Color.	Occurrence and Abundance.	Paragenetic Position.
1. Leadville dolomite and Dyer dolomite.	Impure dolomite; contains carbonaceous matter.			Gray to bluish gray.	Country rock.	Earliest.
2. Recrystallized country-rock dolomite.	Pure and impure dolomite; contains iron in places.	1.680 $\pm$0.002	"Zebra rock," irregular crystalline masses.	White to gray.	Widespread and abundant. "Zebra" structure only in Leadville dolomite.	Variable, principally early.
3. Manganiferous ankerite.	Ankerite with trace of Mn.	1.697 $\pm$0.002	Small individual grains.	Pink.	Sherwood mine. A few crystals.	Early.
4. Epigenetic dolomite.	Pure dolomite.	1.680 $\pm$0.002	Lenses, masses, veinlets.	White to cream.	Widespread and moderately abundant. Merges with (2) in places.	Variable.
5. Ferruginous dolomite.	Dolomite with variable Fe.	1.684 $\pm$0.002	Irregular masses, veinlets.	Cream, weathers tan.	Widespread and moderately abundant.	Variable.
6. Calcite.	Pure calcite.	1.658 $\pm$0.002	Poorly developed rhombohedrons in vugs.	Glassy.	Widespread but in minute amounts, associated with quartz and gypsum in vugs.	Late, possibly supergene.

due, at least in part, to innumerable microscopic veinlets of transecting ferruginous carbonate. As the refractive index (1.697 ± 0.002) agrees closely with one of the indices listed for ankerite, it is concluded that only traces of manganese are present. It is later in age than recrystallization of the country rock and earlier than formation of ferruginous dolomite.

Epigenetic dolomite (4), so called to distinguish it from rock-forming dolomite, is found throughout the area in the carbonate country rocks as well as in the ores; in fact, hardly a cubic inch of either the Leadville or Dyer dolomites is not traversed by one or more tiny white veinlets of dolomite or ferruginous dolomite. In places, however, epigenetic and recrystallized dolomite cannot be distinguished. The ores, occupying brecciated ground within and adjacent to fissures, also contain numerous veinlets and breccia

fillings of dolomite, which in places show more than one stage of growth.

Ferruginous dolomite (5) is mainly epigenetic, although some masses of recrystallized country rock (2) appear to have incorporated iron during recrystallization. Ferruginous dolomite (5) forms veinlets cutting quartz (Fig. 10), silicified or recrystallized dolomite, and dolomite-cemented breccia. It, in turn, is cut by later dolomite veinlets and is replaced by galena. Some specimens from Sheep Mountain contain zoned grains in which the cores are ferruginous dolomite, the margins, pure dolomite.

Interesting relations are observed in aggregates of carbonate and galena from prospects a few feet below the Leadville-Weber (?) contact in Fourmile Gulch. These prospects have been cited as representatives of the most distant facies of mineral deposits in the Leadville region,[24] but they are unique in the area near the London fault. A smooth surface of a specimen from one of the prospects is shown in Fig. 8. The carbonate sequence determined microscopically and megascopically in this specimen is: (1) Leadville dolomite, (2) irregular recrystallization, (3) brecciation, (4) cementation by ferruginous dolomite, (5) brecciation, (6) cementation by dolomite, (7) slight brecciation, and (8) vein stage of ferruginous dolomite and dolomite. Calcite lining vugs but not shown in Fig. 8, represents a ninth stage.

The positions of epigenetic dolomite and ferruginous dolomite in the paragenetic sequence determined in ores from about twenty mines and prospects vary so much that it is deemed impractical to assign these minerals more than a generalized age. Their deposition began early and continued throughout the epoch of mineralization but was, however, nearly concluded before deposition of the later sulphides.

Loughlin and Behre have suggested that epigenetic dolomite in the Leadville district was derived from country rock, especially as the lime-magnesia ratio of country rock nearly coincides with that of the pure dolomite.[25] Their explanation is accepted for the dolomite in this area, but the source of the iron in ferruginous

[24] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, p. 245.
[25] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, p. 253.

dolomite is not so readily apparent. Vanderwilt, in commenting upon a similar occurrence at Aspen, considers that the presence of iron in the carbonates "indicates, or at least suggests, that they are related to the mineralizing solutions that introduced the ore minerals."[26]

Derivation of lime, magnesia, and carbon dioxide, the predominant constituents of all the epigenetic carbonates, from the country rock presupposes partial redeposition of the material attacked and taken into solution during the replacement of country rock by the solutions that deposited ore, gangue, and wall-rock alteration minerals. The largest volumes of country rock have been replaced by jasperoid, smaller amounts by barite, and still less by other minerals; hence, it is significant to note that the bulk of epigenetic carbonates was formed at the same time or shortly after deposition of jasperoid and barite. Masses of cross-cutting carbonate in the Metaline district, Washington are interpreted similarly.[27]

Alteration.

Relative Amounts.—Precise quantitative evaluation of different alteration phenomena would obviously require more data than are available from scattered outcrops and mine workings in formations that are either covered or eroded. Recrystallization and silicification are, however, far more extensive than pyritization and baritization. It should be emphasized, however, that barite is widely distributed in the country rock, in places distant from any ore deposits, particularly in the jasperoid bodies.

Recrystallization.—Variable amounts and kinds of recrystallization, both regional and local, have taken place in the dolomite host rocks. The most conspicuous type is the "zebra" structure so common in the Leadville dolomite. Fig. 9 shows the appearance of a typical fragment, which megascopically consists of alternating sub-parallel bands of white and blue dolomite cut by later veinlets of dolomite with a little quartz. The average grain diameter is

[26] Vanderwilt, J. W.: Revision of structure and stratigraphy of the Aspen district, Colorado, and its bearing on the ore deposits. ECON. GEOL., 30: 239–240, 1935.

[27] Park, C. F., Jr.: Dolomite and jasperoid in the Metaline district, northeastern Washington. ECON. GEOL., 33: 727–728, 1938.

0.3 mm. in the white bands and 0.1 mm. in the blue. The white color resulted from elimination of impurities. In most places contacts between white and blue bands are sharp and irregular, yet local gradations exist. In some specimens the "zebra" structure is transected by later bands of white dolomite that have exceptionally sharp contacts and are bordered by thin selvages (0.01 mm. thick) of opaque impurities. These bands in turn are transected in places by microcrystalline quartz and dolomite. The distribution of "zebra rock" bears no apparent relationship to either structures or ores; Loughlin [28] says that it may be found miles from any center of ore deposition. Solutions doubtless played a role in its origin, but neither their source nor their quantity can be determined.

Another type of recrystallization that occurs in both the Leadville and Dyer dolomites is, in most places, more closely related to brecciation than is the formation of either "zebra rock" or local recrystallization phenomena. It is found at nearly all localities from which specimens were obtained and evidently is just as extensive at a distance from the London fault as close to it. Some sections show recrystallization subsequent to brecciation, others brecciation subsequent to recrystallization, and followed by cementation of the fragments by epigenetic carbonate (Fig. 8). In some specimens, irregular masses of white carbonate are localized by small fractures, but other effects have been so variable that only generalizations are justified. In places, for example, iron has been incorporated during recrystallization to form ferruginous dolomite. In the Leadville dolomite, gradations from "zebra rock" to irregular masses of coarsely crystalline white dolomite may grade further into this type. In both Leadville and Dyer dolomites, distinction between this form of recrystallization and epigenetic dolomite and ferruginous dolomite is not everywhere apparent.

Local recrystallization accompanied deposition of jasperoid, pyrite, and sphalerite. Within jasperoid, recrystallized dolomite occurs in small, irregular, coarse-grained masses. Where related to pyrite or sphalerite, recrystallized dolomite extends from a frac-

[28] Loughlin, G. F.: Personal communication, 1936.

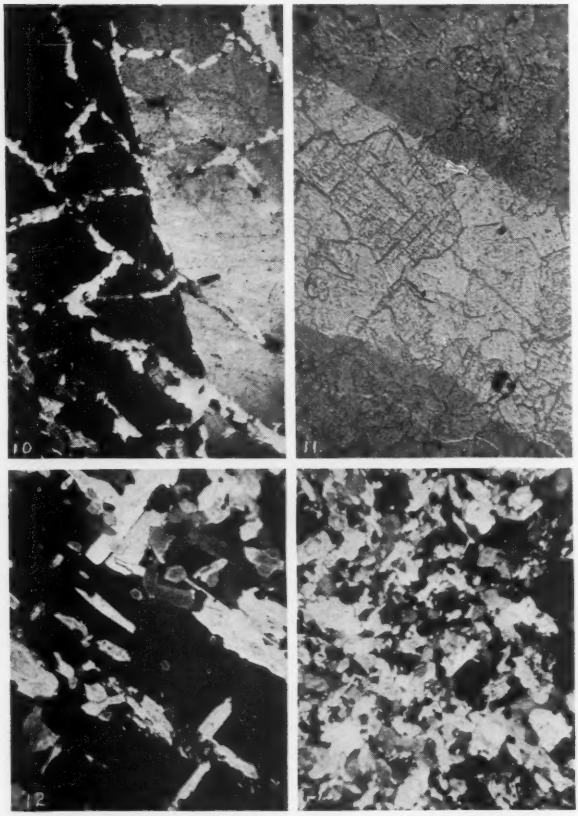

FIG. 10. Intersecting veinlets of ferruginous dolomite in vein quartz (black and gray), showing quartz strain effects and dusty inclusions. Sacramento mine, x-nicols. × 18.

FIG. 11. Local recrystallization of Leadville dolomite. Impurities have been removed from the lighter-colored veinlet with carbonate grains optically continuous across the contact. North of Mudsill mine, plane light. × 160.

FIG. 12. Euhedral type jasperoid showing barite (black) replaced by euhedral quartz. Sheep Mountain, x-nicols. × 18.

FIG. 13. Euhedral type jasperoid. Quartz is finer-grained and zonally arranged carbonate blebs are less prominent than in Fig. 12. South of Big Sacramento Gulch, x-nicols. × 18.

tion of a millimeter to one centimeter away from the sulphide mineral. The chief effect has been removal of impurities, but where zones of recrystallized dolomite coalesce the grain size has been increased. Fig. 11 shows the marginal part of a veinlet that contains medial pyrite outside the photographic field; here, the sharp contact between altered and unaltered rock cuts across crystal boundaries. Some recrystallized zones adjacent to sphalerite have narrow irregular selvages of opaque impurities.

Silicification.

Types.—Flinty jasperoids that were formed by silicification of Dyer or Leadville dolomites are widespread. They range chiefly from brown to gray in color, although some are dark red upon weathering. Many jasperoid bodies are lenses parallel to the bedding that occur in relatively small masses here and there throughout the area (Fig. 25). Exposures are generally incomplete and some specimens were of necessity secured from mine dumps. An extensive mass overlies the old stopes of the Mudsill mine.

Silicified breccias containing angular rock fragments occupy parts of the London fault zone on Pennsylvania Mountain and Sheep Mountain and form an east-trending, dike-like mass east of the London anticlinal axis on Sheep Mountain. This dike-like mass apparently was a feeder to an extensive jasperoid lens 40 feet above the base of the Leadville and a smaller one in the top of the Dyer.

The jasperoids and silicified breccias may be classified into two distinct textural types: (1) euhedral and (2) anhedral, which is the more abundant of the two. These terms have been used by Gilluly [29] to designate types of jasperoids at Mercur and Lion Hill, Utah.

Small cubes of pyrite and pseudomorphs or small irregular masses of limonite are widespread but in minor quantities in the jasperoid bodies. Except in the non-baritic area, platy crystals or aggregates of barite are moderately abundant and are enclosed

[29] Gilluly, J.: Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah. U. S. Geol. Surv. Prof. Pap. 173: 97–101, 1932.

within massive jasperoid or project into cavities. Sericite flakes are microscopically visible in some of the jasperoids from the area between Little Sacramento and Fourmile creeks. Dolomite locally forms masses and veinlets, or is disseminated and in certain jasperoids dolomite occurs as zonal blebs in euhedral quartz grains. Coarser-grained quartz forms veinlets, nodular masses, and drusy coatings of cavities in jasperoid.

Euhedral Type.—Jasperoid composed of euhedral quartz grains is virtually restricted to the eastern slope of Sheep Mountain. It is most extensive on the northeast-trending ridge immediately south of Fourmile Creek. There minor amounts of ore and gangue minerals are associated with jasperoid, recrystallized dolomite, and barite in the Dyer member. Specimens of this jasperoid are not flinty but resemble quartzite impregnated with barite. Under the microscope, euhedral quartz crystals are seen to be cemented by later quartz in optic continuity with euhedral nuclei resulting in an aggregate of subhedral and anhedral grains (Figs. 12, 14). Similar jasperoids have been described from Aspen[30] and Leadville,[31] Colorado; Mercur and Lion Hill, Utah;[32] and northern Arkansas.[33]

Other specimens, collected nearby, illustrate an earlier stage of silicification. In section, skeletal quartz crystals occur in small hexagonal areas of dolomite that have the same texture as dolomite in the surrounding country rock but are more transparent. In none of these, however, does quartz constitute more than 10 per cent of the mass.

Elsewhere, early stages are represented by isolated quartz prisms embedded in recrystallized country rock. In places, the quartz prisms are associated with fragments of strained dolomite embedded in a matrix of fine-grained dolomite. These microscopic relations are analogous to certain pebble dikes at Tintic, Utah,

[30] Spurr, J. E.: Geology of the Aspen mining district, Colorado. U. S. Geol. Surv. Mon. XXXI: 217–221, 1898.

[31] Emmons, S. F., Irving, J. D., and Loughlin, G. F.: *op. cit.*, p. 172.

[32] Gilluly, J.: *op. cit.*, p. 98.

[33] McKnight, E. T.: Zinc and lead deposits of northern Arkansas. U. S. Geol. Surv. Bull. 853: 112, 1935.

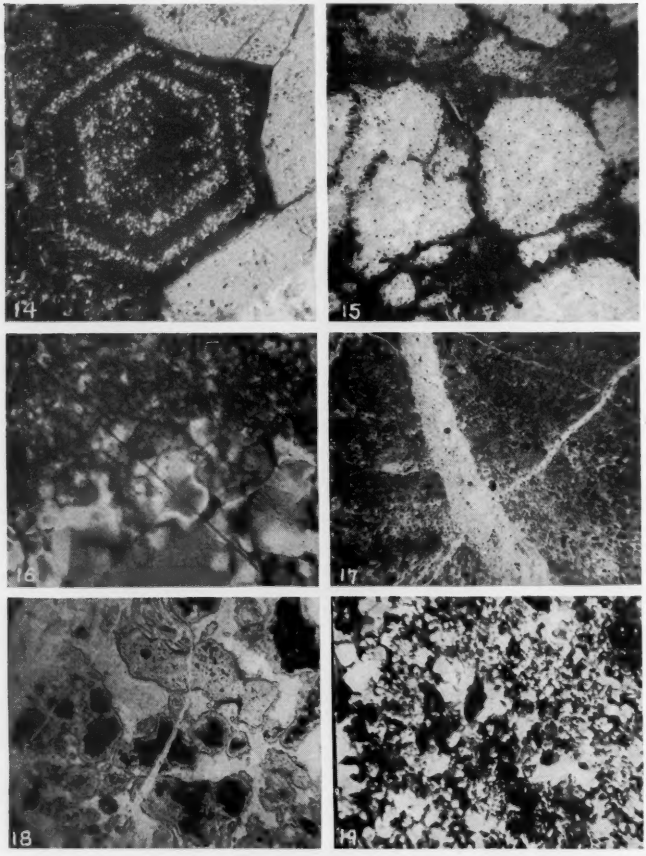

FIG. 14. Typical quartz euhedron of jasperoid with two zones of included carbonate blebs. Nucleus is optically continuous with some of the surrounding quartz, which has produced a subhedral grain with euhedral core. Sheep Mountain, x-nicols. × 170.

FIG. 15. Nodular anhedral facies of jasperoid. Dark is fine-grained quartz with dusty carbonate inclusions; light areas have been recrystallized. Sherwood mine, plane light. × 21.

FIG. 16. Nodular anhedral facies showing contact between fine-grained

which are described as fragmental country rocks in a matrix of either finely divided carbonate "mud" or jasperoid.[34]

The formation of euhedral-type jasperoid began with the elimination of impurities and carbonate from tiny areas of country rock concomitant with introduction of small quantities of silica. With continued introduction of silica, isolated grains of euhedral quartz formed. With further addition of silica, new crystals originated and older ones were enlarged. Eventually, the growing crystals interfered with one another, so that anhedral boundaries were formed.[35] During this process, the host material was not everywhere completely removed. Blebs of carbonate arranged in one, two, or even more crystallographic zones are common in euhedral nuclei, but are not arranged in the accreted anhedral margins (Fig. 14). Euhedral type jasperoid in the Sheep Mountain prospects has replaced barite along cleavage directions, and in turn is veined by ferruginous carbonate.

Anhedral Type.—The anhedral type of silicification, characterized by dominant allotriomorphic texture, is divisible into two facies that have distinctive microscopic characteristics and areal distributions. For descriptive purposes they are termed nodular and granular. The granular facies grades into the euhedral type.

The nodular facies consists either of two generations and sizes

[34] Farmin, R.: "Pebble dikes" and associated mineralization at Tintic, Utah. ECON. GEOL., 29: 361, 1934.

[35] Spurr, J. E.: *op. cit.*, pp. 217–221. Lindgren, W.: Metasomatic processes in fissure veins. A. I. M. E. Trans., 30: 601–602, 1901. Irving, J. D.: Replacement ore bodies and the criteria for their recognition. ECON. GEOL., 6: 556–557, 1911.

quartz of the matrix and coarser-grained quartz of a nodule. Sherwood mine, x-nicols. × 170.

FIG. 17. Veinlet of quartz cutting fine-grained nodular anhedral jasperoid colored by carbonate impuries. Black spots are carbonate. North of Little Sacramento Creek, plane light. × 21.

FIG. 18. Nodular anhedral jasperoid. Masses of fine-grained carbonate and quartz (black) surrounded by masses (gray) containing less carbonate comprise the nodules. Contacts of nodules with irregular quartz (light gray) show narrow rims of dark carbonate. Sharp-walled quartz veinlets transect the whole. North of Little Sacramento Creek, plane light. × 21.

FIG. 19. Same field as Fig. 18. X-nicols. × 21.

of quartz grains or of a single generation and size. In the second variety, tiny nodular masses are outlined by their greater content of carbonate impurities. Where two sizes occur, one forms nodular masses enclosed in the other; and although either generation may constitute nodules, the finer-grained generation is invariably earlier. This facies is found at the Sherwood and Sacramento mines, in prospects north of Little Sacramento Creek, in the silicified breccia of the London fault on Pennsylvania Mountain, and, poorly developed, near the London fault on the south side of Fourmile Creek.

The finest-grained examples are found at the Sherwood mine and in the fault breccia on Pennsylvania Mountain. Fig. 15, from the Sherwood, shows a matrix of grains averaging 0.002 mm. in diameter that enclose nodules composed of variable but somewhat larger-sized grains. Innumerable minute carbonate inclusions impart a brownish color to the matrix in plane light. The nodules are interpreted as recrystallized aggregates rather than as veined and replaced remnants for the following reasons: some sharp-walled carbonate veinlets in the matrix terminate at the nodules; the largest quartz grains are in the centers of the nodules and are nowhere in contact with the matrix (Fig. 16); in a few places, rows of grains within the nodules at the contact with the matrix are arranged normal to the boundary.

Specimens from other places show various modifications of these as well as contrasting features. None, however, shows well-developed spherulitic or chalcedonic textures, even where fine-grained quartz constitutes the nodules. Some undulatory extinction is visible at the margins of fine-grained nodules from the Pennsylvania Mountain occurrence. One thin section shows coarser quartz forming not only nodules enclosed in, but also veinlets transecting finer-grained quartz full of unoriented carbonate specks (Fig. 17). Directional crystallization perpendicular to the walls is exhibited in some of the veinlets and in some of the nodules. In another thin section, irregular-shaped nodules of diverse sizes have dark nuclei, composed of fine-grained quartz containing profuse carbonate specks, surrounded by somewhat

lighter quartz with fewer inclusions (Figs. 18, 19). The nodules, in turn, are surrounded by slightly coarser-grained and clearer quartz. Particularly interesting in this section are dark films of concentrated carbonates along the margins of the nodules. Veinlets of still clearer and coarser quartz transect matrix, nodules, and marginal films. In thin sections of several specimens from the Sacramento mine, the nodules for the most part are composed of dark, medium-grained quartz, colored by minute carbonate specks (Fig. 21), but a few have cores of residual carbonate in clear quartz (Fig. 20). Moreover, the coarser, transparent quartz enclosing and transecting the nodules, in a few places, contains quartz grains surrounded by carbonate rims that doubtless represent original specks segregated during the supposed recrystallization process.

The "granular" facies occurs south of Little Sacramento Creek. It comprises the jasperoid lenses in the Dyer dolomite at the Mudsill mine and on the north slope of Sheep Mountain as well as lenses in the Leadville dolomite south of the peak of Sheep Mountain.

The texture as revealed under the microscope consists of poorly terminated quartz laths embedded in finer-grained, anhedral quartz (Fig. 23). These are thought to represent two generations in which the second was not derived by recrystallization from the first. Although isolated, residual carbonate masses exist, individual quartz grains contain neither the blebs found in the euhedral-type nor the minute specks so profuse in the "nodular" facies. The only exception is a jasperoid in the Manitou limestone on the north side of Sheep Mountain, where some few quartz laths contain traces of oriented carbonate blebs.

Near the Mudsill mine the jasperoid contains fewer and smaller quartz laths than a few hundred feet farther east. South of the summit of Sheep Mountain, in turn, the laths are still larger and more numerous, and some are even prismatic. In the matrix, too, there is a general, slight increase in grain size south and southeastward from Little Sacramento Creek. Fig. 24 shows a variety of the granular anhedral type transitional towards the euhedral type where the matrix forms only a small portion of the whole.

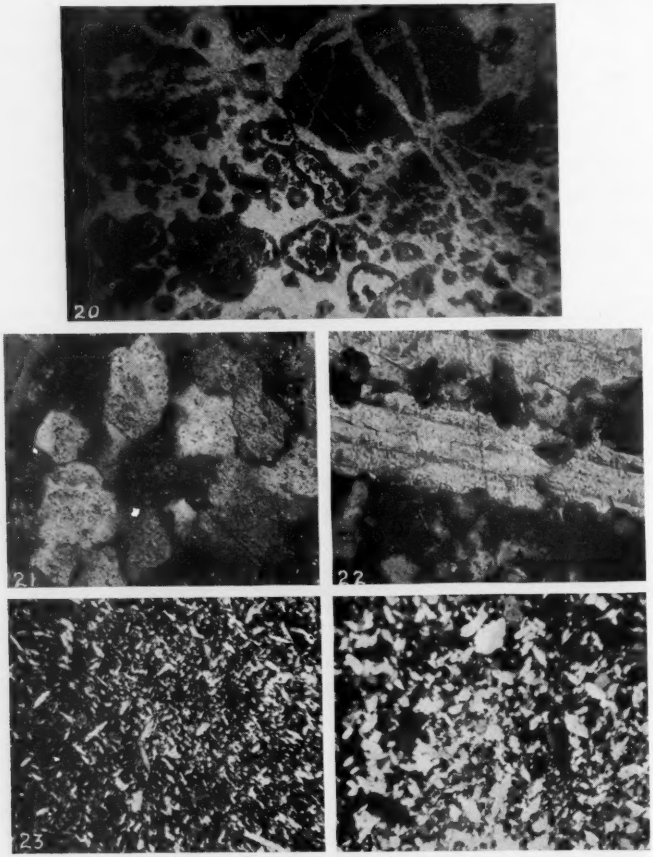

FIG. 20. Nodular anhedral jasperoid. Dark areas, fine-grained quartz with carbonate inclusions; light areas, coarser quartz. Carbonate in center is surrounded by clear quartz. Sacramento mine, plane light. × 25.

FIG. 21. Nodular anhedral jasperoid. Section of nodule shows anhedral quartz containing carbonate inclusions. Sacramento mine, x-nicols. × 200.

FIG. 22. Detail of replacement of barite (light gray) by granular anhedral jasperoid. A replacement veinlet of quartz is shown within the

Barite, which is abundant in jasperoids on Sheep Mountain, exhibits the effects of strain and brecciation and has been corroded by the matrix quartz. Every barite plate retains its gross crystal outline but possesses ragged margins that are due to the replacement by quartz (Fig. 22). Identical relations in the jasperoids at Mercur, Utah have been described by Gilluly.[36] The quartz laths, in the Horseshoe and Sacramento areas, have corroded margins similar to those of barite, and the fine-grained matrix appears to replace them.

The silica of the jasperoids is rarely in contact with vein quartz. In the silicified breccia of the London fault on Pennsylvania Mountain, however, an early generation of coarse vein quartz has been brecciated and replaced by nodular jasperoid silica. Furthermore, within the Dyer dolomite on the north side of Sheep Mountain, a few pods of coarse vein (?) quartz replace barite, and both barite and quartz show strain effects, brecciation, and replacement by the laths and matrix of the anhedral jasperoid.

Distribution and Origin.—In general, jasperoids have formed in two textural types, euhedral and anhedral;[37] by either of two methods of silica transport, hydrothermal or colloidal.[38] They are characterized by either sharp or gradational contacts with the carbonate host rock.[39] The sharp contacts appear to have been caused by a "wave" of alteration throughout the rock mass, which Lindgren attributes to replacement by colloidal silica. Conversely, transitional contacts are generally believed to be due to

[36] Gilluly, J.: *op. cit.*, p. 100.

[37] Gilluly, J.: *op. cit.*, p. 98.

[38] Lindgren, W.: Processes of mineralization and enrichment in the Tintic mining district. ECON. GEOL., 10: 225–240, 1915.

[39] Irving, J. D.: *op. cit.*, pp. 555–559.

barite crystal parallel to a cleavage direction. The edge of the barite crystal has been corroded. Ridge, south of Sheep Peak, x-nicols. × 200.

FIG. 23. Granular anhedral jasperoid. Poorly developed quartz laths are embedded in fine-grained quartz. Near Mudsill mine, x-nicols. × 25.

FIG. 24. Granular anhedral jasperoid. A transition towards euhedral jasperoid (Fig. 13) showing coarse quartz prisms rather than laths. Continued quartz deposition resulted in fine-grained matrix. Ridge southeast of Sheep Peak, x-nicols. × 25.

hydrothermal solutions. In the bedded jasperoid masses, selective hydrothermal replacement may have produced the sharp contacts.

The textures produced by the silicification display an asymmetric zoning eastward from the London fault and also southward along the fault from the Sherwood mine. Anomalies exist,

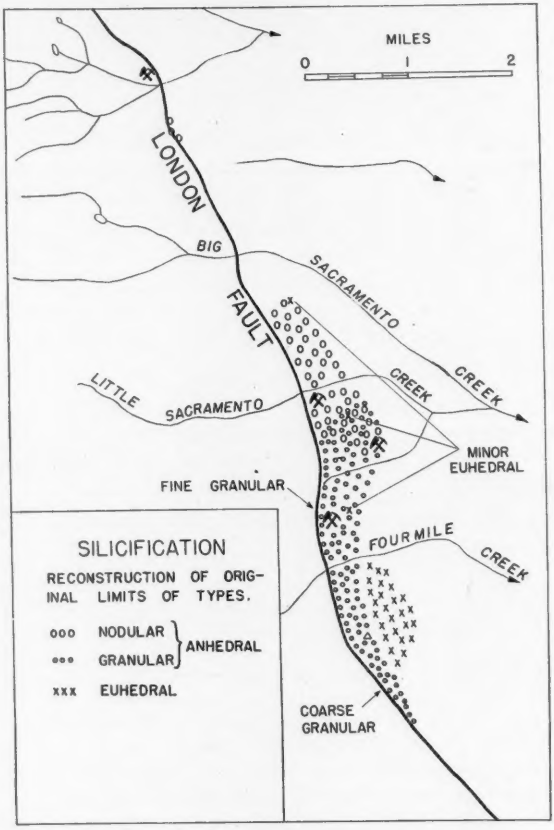

FIG. 25. Distribution of jasperoid types. The bulk of the nodular anhedral type lies north of the granular anhedral. Euhedral occurs principally on Sheep Mountain. Boundaries approximate.

but they do not invalidate the concept, for as suggested by Loughlin and Behre,[40] perfect lateral zoning is not to be expected in a region of complicated structure. The general distribution of types and facies is shown by Fig. 25. In summary, the nodular facies occurs in general north of, but overlaps the granular facies, which in turn occurs north and west of the euhedral type. Moreover, both facies of the anhedral type show a progressive increase in grain size eastward and southeastward from the Sherwood mine.

The cause of the zonal pattern is speculative. Rock pressure could have played little part, for the deposits are found through a small vertical range, and solution pressure is an enigma. The effects of differences in temperature cannot be evaluated, although Lindgren considers that a higher temperature caused increased grain size and absence of colloidal characters in the southern part of the Tintic district.[41] Gilluly questions this as a generalization and notes that other factors may be influential in governing the boundary between colloidal and crystalline precipitation of silica.[42]

Temperature differences seem less important than differences in available silica, which could be due to variations either in the quantity of solutions or in their concentrations. It seems probable that the silica where in least concentrated solutions formed isolated crystals; where somewhat more concentrated it formed subhedral or anhedral aggregates of grains in optical continuity with nuclear euhedrons; where still more concentrated, innumerable new centers of crystallization produced anhedral grains not in optical continuity with the laths; even greater concentrations resulted in fewer original laths and smaller grains owing to more centers of crystallization; and the greatest concentrations yielded extremely fine-grained aggregates that later were partly recrystallized to coarser grains.

The importance of colloids in ore deposition has for some years

[40] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, p. 254.

[41] Lindgren, W. and Loughlin, G. F.: Geology and ore deposits of the Tintic mining district, Utah. U. S. Geol. Surv. Prof. Pap. 107: 158, 1919.

[42] Gilluly, J.: *op. cit.*, p. 101.

been strongly advocated by Lindgren, who believed [43] that silica, throughout its hydrothermal range, is precipitated as a gel. According to Lindgren, only slight variations may at times determine whether fine-grained metacolloids or well-developed crystals result from the gels, but crystallization in general proceeds more rapidly the higher the temperature; consequently, the question naturally arises as to the mode of transportation and deposition of the silica in the area here described.

The euhedral jasperoid shows gradational contacts of the type generally regarded as characteristic of replacement; moreover, carbonate blebs oriented in one or more zones parallel to crystal faces within the euhedrons suggest slow growth of crystals that at times were unable to eliminate all impurities. These features can be readily explained by direct deposition from solutions, but would be very difficult to explain, at least on the basis of present knowledge, as derived from colloids.

The evidence regarding the granular facies is less convincing, but for it likewise, direct precipitation from solution is the preferred explanation. In many places this type has sharp contacts with adjacent beds but lateral terminations within the bed that has been replaced were not visible. Local gradations toward the euhedral type have been found and are characterized by quartz laths that contain a few carbonate blebs. At the Mudsill mine the granular facies is underlain by the euhedral type. It is believed that this is a mixed type and is transitional towards the euhedral type. The initial stage consisted of the hydrothermal formation of quartz crystals followed by replacement of the matrix by fine-grained quartz. A somewhat similar history has been postulated for quartz and micro-granular silica around orebodies.[44] There are no evidences of recrystallization or crystallization from a colloid.

Contact relations of the nodular facies are nowhere well-displayed. The fine-grained generation of quartz may well be a metacolloid, particularly as, in places, it contains tiny ramifying

[43] Lindgren, Waldemar: Succession of minerals and temperatures of formation in ore deposits of magmatic affiliations. A. I. M. E. Tech. Pub. 713: 9, 20, 1936.

[44] Riley, L. B.: Ore-body zoning. ECON. GEOL., 31: p. 179, 1936.

cracks that may be ascribed to desiccation; however, fibrous material is virtually absent. The fineness of grain, moreover, constitutes no certain proof of colloidal deposition. It could be due to very rapid deposition with many crystallization centers.

It is believed that a comprehensive investigation of jasperoids presents a fertile field for research in the behavior of siliceous solutions. It is indeed surprising that this phase of wall-rock metasomatism has been so little investigated especially in view of its occurrence in most limestone districts. A few words of caution may be interposed for the benefit of other workers. Jasperoids in a given district may or may not show areal variations. The causes of the variations are yet only a subject for conjecture. In order to furnish an adequate basis for microscopic work, the masses should be as accurately mapped as if they were valuable orebodies and should be systematically sampled for petrographic variations.

Paragenesis.

The paragenetic relations for hypogene ore, gangue, and alteration minerals are set forth in Fig. 26. It will be noted that the most conspicuous uncertainties, owing to lack of textural evidence, are those of vein and jasperoid quartz.

Zonal Relations.

Evidence for lateral, vertical, or conical zoning in a mining district may include the following features: chemical changes expressed by variations in mineralogy, chemical changes expressed by variations in composition of individual mineral species, variations in textural or other physical properties of the ores. It is possible, moreover, to express zoning by any one of several features or by more than one, provided that there are suitable directional manifestations of variability.

Areal variations in the Horseshoe and Sacramento districts are indicated by Figs. 25, 27, and 28. The most conspicuous mineralogic variation is shown by barite, but there also are noteworthy variations in quantitative distribution of pyrite, tennantite, argentite, and quartz. The preferential associations, argentite-

tennantite in the productive area, and argentite-galena with only minor tennantite in the unproductive area cannot be explained. Comparatively greater quantities of argentite and tennantite in

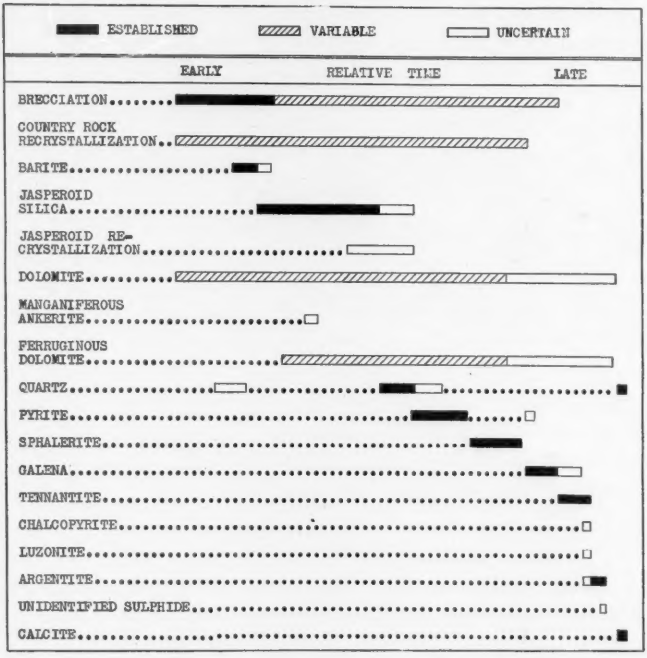

FIG. 26. Generalized paragenetic positions indicated by vertical order from top to bottom. Particular relations of individual minerals shown by horizontal boxes. Those indicated as variable occupy different or repeated positions at different places. Areas of boxes have only semi-quantitative significance.

ores north of Fourmile Creek result in higher $\frac{Ag + Cu}{Pb}$ ratios than in the unproductive area to the south. Chemical changes of individual mineral species are indicated by the variations in color of sphalerite, and by the manganese content of some carbonate.

Textural variations are exhibited conspicuously by jasperoid silica; less conspicuously by pyrite. The areal relations and the extent of most of these variations have been previously discussed. Each variation, however slight, points to a center in the vicinity of the Sherwood mine.

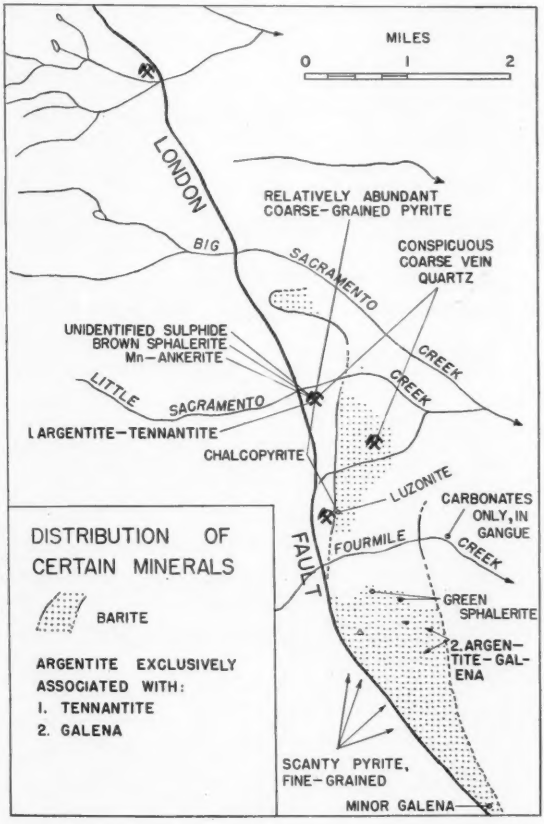

FIG. 27. Distribution of certain minerals. Note how the western edge of the barite zone lies east of the London fault in the northern part of the area.

The productive area, as related to the zoning, includes the entire inner, non-baritic area and extends into the baritic zone. The central and outer parts of the baritic zone, however, have been non-productive. North of the Sherwood mine is a barren area whose existence is not explained by the zonal pattern.

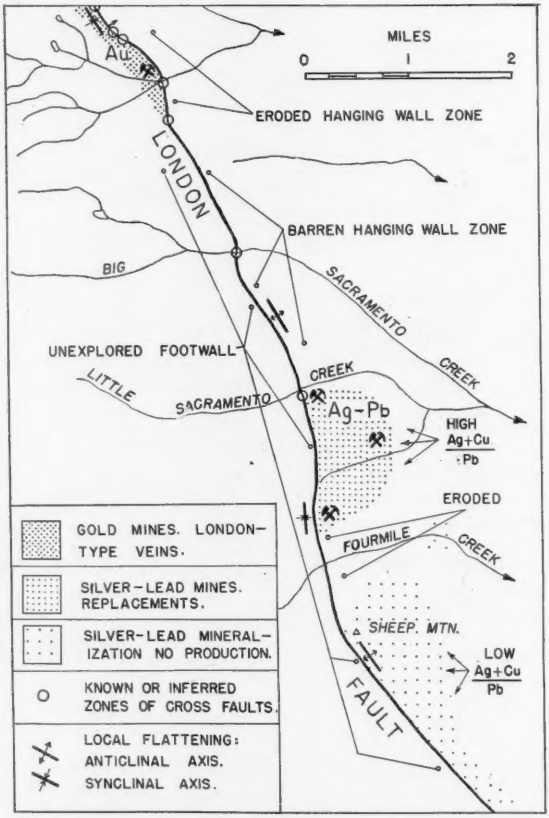

FIG. 28. Production along the London fault. Gold-quartz veins lie in the footwall at the north; the area of silver-lead replacements in the hanging wall to the south has been productive between Fourmile and Little Sacramento creeks and elsewhere is widely but poorly mineralized.

Loughlin and Behre[45] have classified the ores of the western side of the Mosquito Range into five temperature facies, three of which are represented in the Horseshoe and Sacramento districts. The coolest facies is represented by the galena-carbonate mineralization in a few prospects in the lower part of Fourmile Creek; these have been correlated with the "telethermal" ores of Weston Pass.[46] Next are the "cooler mesothermal" facies, represented by the baritic ores, which are very similar to the "replacement bodies along fissures in Blue limestone . . . of resinous to pale green zinc blende and galena, with variable though small quantities of pyrite and even smaller amounts of chalcopyrite in a gangue of jasperoid, crystalline quartz, dolomite, and barite" found outside the Leadville district.[47] The "intermediate mesothermal" facies is represented by the non-baritic ores; however, tennantite and argentite are moderately abundant and the sphalerite contains no chalcopyrite blebs even in the Sherwood ores, so they doubtless represent only the outer part of the Leadville "intermediate mesothermal" zone.

Textural variations of the jasperoids are in harmony with the zonal concept. The nodular facies of anhedral jasperoid occurs for the most part in the "intermediate mesothermal" zone. Anhedral granular jasperoid occurs in the "cooler mesothermal" zone and becomes coarser grained southward. The euhedral type is most widely distributed on Sheep Mountain. This pattern of distribution (Fig. 25) shows that the finest textures lie parallel to the deposits of highest thermal affinities and the coarsest textures parallel to those of lower thermal affinities.

It may appear anomalous to propose that textural variations of the jasperoids were caused by differences in concentration of the solutions whereas the foregoing discussion intimates that thermal conditions controlled distribution of barite and sulphides. The broad conception of a zone will allow, however, certain chemical, mineralogic, and textural characteristics that may be caused by any combination of the influential factors of temperature, pres-

[45] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, pp. 222–240.
[46] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, pp. 240–245.
[47] Loughlin, G. F. and Behre, C. H., Jr.: *op. cit.*, p. 231.

sure, or composition of solutions. Concentration of the siliceous solutions seems the most reasonable explanation for variations of jasperoid texture inasmuch as the coarsest textures formed at the lowest temperatures. Mineralogic variations between the baritic and non-baritic ores are more directly attributable to thermal conditions. Within the "cooler mesothermal" zone, however, where the mineral composition is virtually constant, the observed differences between productive mines and unproductive prospects are attributed to quantitative differences between solutions. Evidence shows that the area south of Fourmile Creek received little metallization, owing to small amounts of solutions and low concentrations.

Regional Relations.

The known mineralization associated with the London fault consists of: (1) small silver-lead replacement orebodies in the Leadville dolomite on New York Mountain, about three-eighths of a mile north of the northernmost London mine workings; (2) extensive gold-quartz veins in porphyries and some gold-quartz veins in the Leadville dolomite, extending more than two miles along the fault in the London mine workings; and (3) small silver-lead replacement orebodies in the Leadville and Dyer dolomites in the Horseshoe and Sacramento districts. The first two are on the western or footwall side of the fault, and the third on the eastern or hangingwall side. The Sherwood mine, northernmost of the third group, lies approximately three miles south of the London workings. Brown's Pass, southern visible limit of mineralization, is four miles south of the Sherwood mine.

The relatively small size of prospects, the slight metallization, and the mineral relations show that very little silver was introduced in the area east of the fault and south of Fourmile Creek. Rich silver ores are not to be expected there, but in a locale of favorable structure, small lead orebodies low in silver content may occur. Between Fourmile and Little Sacramento creeks, there are possibilities of further small lead-silver discoveries, particularly in the Leadville dolomite on both sides of the anticline east of the London fault. A number of divergent faults of small magnitude

doubtless cross this area, although only a few are visible. The three productive mines are situated here, and besides, numerous mineralized prospects attest to the scope of solution activity. It may be especially noted that except along the sides of the gulches, the Leadville dolomite has not been prospected at depth adjacent to the fault. Still farther north, the hangingwall of the fault offers no visible encouragement.

Footwall relations south of the southernmost workings of the London mine provide the principal economic and geologic interest in the area, though prospecting will be expensive because of the depth to favorable horizons. As stated, ores in the hangingwall show progressively higher thermal affinities northward. Gold ore in the London mine, three miles north of the Sherwood mine, shows yet higher thermal affinities though it is also classed as "intermediate mesothermal."

The viewpoints can, therefore, be entertained that the center of mineralization at the Sherwood mine constitutes the uppermost expression either of a separate center of mineralization or of a center zonally related to the London Mountain center. In any event, the main channel of ore-forming solutions was situated below the Sherwood mine, and solutions migrated southward, eastward, and upward in the hangingwall of the London fault.

Configuration of orebodies in the London mine has led to the conception that mineralizing solutions were there confined to the footwall of the London fault. The suggestion that the Sherwood and other ores east of the fault were deposited by solutions that leaked through the fault and, once having gained access to the hangingwall, spread over a wide area holds considerable force.[48] It seems logical to assume that ore-depositing solutions were largely confined to the footwall. The postulated break-through near the Sherwood mine is probably related to the suspected transverse fracturing there. It can be stated that solutions traversed the broken footwall zone far below the Sherwood mine but field and mineralogic studies have not served to clarify the problem of

[48] Singewald, Q. D. and Butler, B. S.: Structure and mineralization along the London fault, Colorado. A. I. M. E. Trans., 126: 440–441, 1937.

extension of the London ore zone southward in the footwall because the observed zonal pattern in the hangingwall can be treated either by relating it to the London center or, with equal justification, by ignoring the London center.

If the Sherwood center represents an outlying manifestation of the London center, solutions formerly moved in the footwall in the interval between, whereas, if the Sherwood is indeed a separate center, solutions moved in the footwall, but not with continuity into the London Mountain area. Under either interpretation the deformed zone adjacent to the footwall of the fault provided channelways, but whether these were in a suitable environment for ore deposition cannot be foretold.

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GEOLOGY AND GROUND-WATER RESOURCES OF THE "EQUUS BEDS" AREA IN SOUTH CENTRAL KANSAS.[1]

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ABSTRACT.

This paper summarizes the results of a detailed investigation by the U. S. Geological Survey in cooperation with the Kansas State Geological Survey, Kansas State Board of Health, and the City of Wichita. The geology of the area has been remapped, and several new formations have been established, including the Emma Creek formation of middle and upper Pliocene age, and a thick loess deposit. The hydrologic studies involved extensive test drilling and resulted in the development of a new ground-water supply for the City of Wichita.

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[1] Presented before the Society of Economic Geologists, Minneapolis Meeting, Dec. 28, 1939. Published by permission of the Director of the Geological Survey, U. S. Department of the Interior, and of the Director of the Kansas State Geological Survey.

INTRODUCTION.

THE so-called Equus beds area in south-central Kansas embraces those parts of McPherson, Harvey, Reno, and Sedgwick Counties underlain by beds formerly classified as the McPherson formation, but commonly called the "Equus beds." *Equus* is the generic name of a Quaternary horse, the bones and teeth of which have been found in these deposits. The location of this area is shown in Fig. 1.

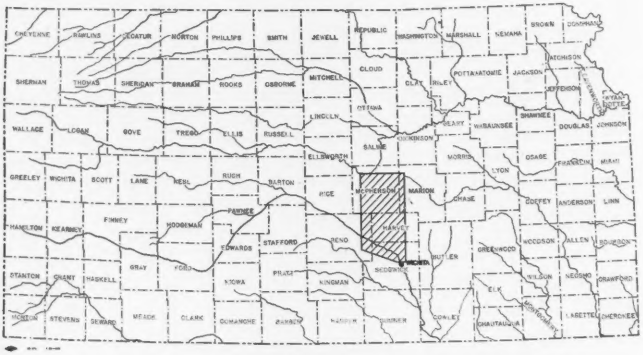

FIG. 1. Index map of Kansas showing the location of the "Equus beds" area.

Attention was first focussed upon these deposits as productive sources of ground water in 1897, by Haworth and Beede.[2] They have long been utilized as sources of public-water supply by the cities of McPherson, Galva, Canton, Inman, Buhler, Moundridge, Halstead, and Newton and have long been regarded as a possible source of supply for the City of Wichita, located at the south end of the area.

The discovery and development of several large oil fields in the area presented a new hazard to the valuable ground-water supplies, for, owing to improper methods of disposal, a large quantity of brine produced with the oil eventually found its way into the

[2] Haworth, E., and Beede, J. W.: The McPherson Equus Beds. Kansas Univ. Geol. Surv., 2: 295, 296, 1897.

underground reservoirs. These and other problems led, in July 1937, to a detailed investigation by the United States Geological Survey in cooperation with the Kansas State Geological Survey, Dr. R. C. Moore, Director; and the Division of Sanitation of the Kansas State Board of Health, Prof. Earnest Boyce, Chief Engineer. The investigation was made under the general direction of Dr. O. E. Meinzer, Geologist in Charge of the Division of Ground Water of the Federal Survey. During the first year the work was under the immediate supervision of David G. Thompson of the Federal Survey, who planned many details of the investigation. Beginning in 1938 the investigation was under the immediate supervision of S. W. Lohman, of the Federal Survey, as Mr. Thompson's services were required in connection with other work.

The writers were ably assisted in the collection of basic field data by the following temporary employees of the Federal Survey: R. S. Delamater, G. H. von Hein, Fred T. Holden, Bruce F. Latta, James I. Nelson, and James Tandy. The manuscript was read critically by Doctors O. E. Meinzer and R. C. Moore, and the geologic names were checked by Miss Alice S. Allen, secretary of the Committee on Geologic Names, United States Geological Survey.

The investigation of the "Equus beds" area was greatly enlarged and altered somewhat in scope during the summer of 1938, when the City of Wichita also began financial cooperation with the State and Federal Geological Surveys and the State Board of Health. The water supplied to the City at present is quite hard and high in chloride. The City's purpose was to enlist State and Federal aid in determining whether a sufficient quantity of soft, fresh water could be obtained within an economic distance to supply the needs of the city. The renewed interest in the "Equus beds" as a source of water supply was occasioned by the possibility of obtaining government aid in financing the development of a new water supply. Long before all phases of the ensuing investigation were completed, the City's consulting engineers were convinced that the required quantity of fresh and relatively soft water was obtainable in an area underlain by thick alluvium south

and west of Halstead, about 22 miles northwest of Wichita. Twenty-five permanent wells have been drilled and tested, and a pipe line and other works for conducting the water to the City are now under construction.

The present report deals briefly with the general geology and principal hydrologic features of the area. The details will appear later in a more comprehensive report now in preparation.

GEOLOGY.

Summary of Stratigraphy.

In 1897, Haworth and Beede [3] described and mapped a series of deposits in this area which they referred to the Pleistocene and named the McPherson Equus beds. On the geologic map of Kansas [4] issued in 1937, a large part of the sand dune area and the alluvium along the Arkansas River were distinguished from the McPherson formation or "Equus beds," but the original mapping in the northern part of the area was accepted with little or no change.

During the present investigation it became apparent that a further subdivision of the "Equus beds" was necessary to a proper understanding of the geology and hydrology of the area. The geology of the area was remapped by John C. Frye, and the results are shown in Fig. 2.

The rocks of the "Equus beds" area are all of sedimentary origin and range in age from Permian to Quaternary. The oldest outcropping formation, the Permian Wellington formation, is exposed only along the eastern border of the area; the Permian Ninnescah formation is exposed along the western and northern borders; and the Cretaceous Dakota group is exposed in the northeastern corner. The remainder of the area is occupied by Tertiary and Quaternary formations. Most of the formations are poorly exposed, as the area is quite flat in most places.

A generalized section of the geologic formations, incorporating revisions of classification and nomenclature of Permian beds re-

[3] Op. cit., pp. 287–296.

[4] Geologic map of Kansas. Kansas State Geol. Surv., 1937.

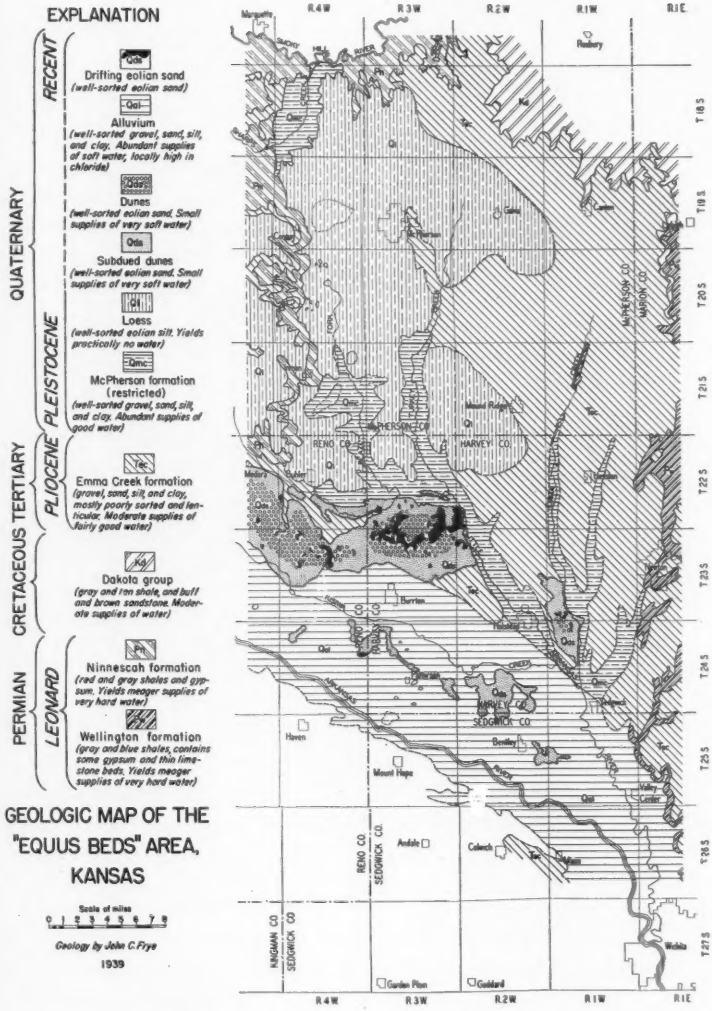

FIG. 2. Geology of the "Equus beds" area, Kansas.

TABLE 1.

GENERALIZED SECTION OF THE GEOLOGIC FORMATIONS IN THE "EQUUS BEDS" AREA.

Era.	System.	Series.	Subdivisions.		Thickness.	Physical Character.	Water Supply.
Cenozoic	Quaternary	Recent and Pleistocene	Dune sand		0–100	Cross-bedded eolian sand. Several cycles set apart by soil zones.	Will not yield large supplies owing to fineness of sand. Forms important area of recharge for adjacent formations.
			Alluvium		0–300	Gravel, sand, silt and clay: tan to buff; Rocky Mountain types predominate.	Most productive source of water in area. Yields large supplies of water. Water of good quality except near Arkansas River and where contaminated by oil-field brines.
		Pleistocene	Loess		0–110	Brown, tan, and gray loess. Volcanic ash occurs locally at the base; bands of lime nodules occur through the deposit.	Yields little or no water and prevents or hinders recharge of underlying formations.
			McPherson formation (restricted) (Kansan ? stage)		10–150	Gray to tan outwash sand and gravel as channel fillings, and locally derived laminated silts.	Yields large supplies of good water.
	Tertiary	Pliocene	Emma Creek formation		10–180	Brown, buff, and gray channel sand and gravel, and floodplain sandy silt and clay. Mostly from a Dakota source, locally interbedded with Rocky Mountain types.	Yields only fair quantities of water. Water of good quality except where contaminated by oil-field brines.
Mesozoic	Cretaceous		Dakota group [a]		50–400	Cross-bedded buff to brown sandstone, in the main friable, contains a few gray quartzite beds; overlying blue-gray, tan and buff shale and siltstone, with a few sandstone beds.	Crops out only in corner of area, no data obtained. Sandstones will probably yield moderate supplies of potable water.
Paleozoic	Permian [a]	Leonard [a]	Sumner group	Ninnescah shale	0–250	Red and gray shale and siltstone, contains some thin limestone beds and gypsum.	Yield small supplies of very hard water.
				Wellington formation	115 +	Vari-colored shale with clay and gypsum; limestone beds at top.	

[a] Classification of the Kansas State Geological Survey.

cently made by the Kansas State Geological Survey, is shown in Table I.

Tertiary and Quaternary Geologic History.

The Tertiary history of the "Equus beds" area was initiated by an extensive period of subaerial erosion. Although the courses of many of the eroding streams have not been determined with certainty, the major aspects of this Tertiary drainage pattern seem apparent. Streams were flowing from the west across the western part of Kansas, finding outlets to the south and east. Immediately to the east of this area the major streams drained to the southwest. It is possible that there were one or more streams flowing south from the location of the present Smoky Hill River to the valley of the present Arkansas River.

In late Tertiary time the streams flowing from the west, crossing the western half of Kansas, became incompetent to transport their loads and began to deposit sediments derived from the Rocky Mountains. Deposition in the "Equus beds" area may have started contemporaneously with Ogallala sedimentation farther west, or shortly thereafter.

The Tertiary topography appears to have been modified appreciably by solution of salt in the Permian Wellington formation. As this formation dips toward the west, it is probable that the salt was dissolved back some distance from the outcrop prior to Tertiary time. Additional solution probably occurred when the Tertiary streams approached their maximum development and were vigorously cutting their rock floors. This solution produced a depressional area, parallel to the strike of the salt beds extending between Halstead and McPherson. During certain intervals this depression apparently contained a body of slack water in which were deposited the lower gray and brick-red clays and silts of the Emma Creek formation.

During Emma Creek time the streams from the north and northeast laid down floodplain and channel deposits over the lake beds and adjacent areas. A few times during this interval deposition by streams from the west became dominant as indicated by the interfingering of their deposits with those from the north and

• Classification of the Kansas State Geological Survey.

northeast. Deposition of the Emma Creek sediments began in middle Pliocene time and may have extended into early Pleistocene.

At the close of Emma Creek sedimentation there appears to have been a through valley or depression extending south from a point near Lindsborg past McPherson to the Arkansas Valley, and this valley may have contained a through-flowing stream. At this time the Kansan glacier dammed the Kansas River northeast of the area. When this glacier began to melt, excessive quantities of melt water filled the Smoky Hill Valley and found an outlet through the "McPherson Valley," ultimately joining the ancestral Arkansas Valley. The glacial outwash carried by this stream was deposited to form the McPherson formation (restricted).

The Arkansas River in Kansan time probably flowed north of Bentley and Patterson and south of Halstead and Burrton, occupying a position close to that of the present Kisiwa Creek. A bedrock ridge occurs between this filled and abandoned valley and the present filled valley to the southwest. As the material supplied by the glacial melt water was greater than the streams could continue to transport, the ancestral Arkansas Valley was filled with outwash from the west at about the same time that the McPherson formation was being deposited. When the ice had retreated entirely from Kansas, the valley of the present Kansas River had a lower outlet than the filled McPherson channel; hence the ancestral Smoky Hill drainage was captured by the Kansas River, and the stream occupying the "McPherson Valley" gradually dried up. During and immediately after the deposition of the McPherson channel deposits, silts were deposited in the tributary valleys.

Dunes began to develop early in the Pleistocene on the Emma Creek surface east and north of Hutchinson and east of Halstead. There is evidence of three and probably four cycles of dune development in the Hutchinson area. The most recent cycle is indicated by shifting sands at the present time.

Loess occurs over a large part of the central "Equus beds" area. Although the thin mantle of loess that is spread over nearly

the entire area is Recent, the thick body of loess accumulated during the latter part of the Pleistocene. The loess was deposited on Emma Creek and McPherson beds, and its basal portion contains beds of volcanic ash.

Deposition of the material underlying the Arkansas alluvial plain was initiated in late Tertiary time. Deposition in this area has continued intermittently to the present. The progressive subsidence of the bedrock floor under the Arkansas valley has trapped a more continuous sequence of deposits than occur elsewhere in the "Equus beds" area, and there is evidence that subsidence is still in progress in some places between Mt. Hope and Inman. The master stream has shifted once and probably twice across the divide between the two bedrock valleys.

WATER-BEARING FORMATIONS.

Permian Rocks.

Subdivisions and General Features.—The bedrock floor under most of this area consists chiefly of Permian shale, with some limestone and gypsum. The Wellington formation includes the oldest rocks exposed or penetrated in test holes, and crops out along the eastern edge of the area shown in Fig. 2. Ver Wiebe,[5] and more recently Norton,[6] have described the Wellington formation in this area. The Hutchinson salt bed in the Wellington is not exposed, but from subsurface studies is known to underlie a considerable part of the area.

The Wellington formation consists of blue, gray and red shales, with some siltstone, gypsum and limestone. The rocks for the most part are thin bedded. Local minute folding and crinkling is common. The maximum exposed thickness of this formation in the area mapped is 115 feet.

The Wellington formation is conformably overlain by the Ninnescah shale,[7] which crops out in a belt extending north of Hut-

[5] Ver Wiebe, W. A.: The Wellington formation of central Kansas: Univ. of Wichita, Bull., 12 (5): 1–18, 1937.

[6] Norton, G. H.: Permian redbeds of Kansas. A. A. P. G., Bull. 23: 1758–1767, 1939.

[7] Norton, G. H.: op. cit. pp. 1767–1774.

chinson and along the south side of the Smoky Hill Valley. This formation consists mainly of red shale and siltstone with a few beds of gray shale, red sandstone, and some gypsum. The gypsum occurs in crosscutting and intersecting veins. The shale for the most part is thin bedded and weathers rapidly on exposed slopes. The Ninnescah attains a maximum thickness of 250 feet in the western part of the area, and because of erosion of upper beds thins rapidly to the east and southeast. The regional dip of the Permian rocks is toward the west, and the salt beds thicken toward the west.[8]

Water Supply.—The Permian rocks consist largely of shale and in general are poor water bearers. The water generally occurs in minute crevices in the shale, although locally it is obtained from somewhat larger openings in thin beds of limestone. Scanty data indicate 40 or 50 gallons a minute to be the probable maximum yield obtainable from wells in these formations. Owing to the high content of gypsum in the rocks, most of the waters are excessively hard and highly mineralized. The hardness ranges from about 500 parts per million to nearly 1,200 parts.

Cretaceous Rocks.

General Features.—Rocks included within the Dakota group[9] of Cretaceous age unconformably overlie the Wellington and Ninnescah formations. These rocks are well exposed in the maturely dissected area north and east of Canton. The Dakota group here consists of buff, tan, and gray shales and siltstones, overlain by cross-bedded brown and buff friable sandstone, including a few beds of light gray quartzitic sandstone. The Dakota group in this area attains a maximum thickness of 400 feet.

Water Supply.—No definite information was obtained in regard to the quantity and quality of water obtainable from the Cretaceous rocks in this area. The municipal wells at Canton

[8] Bass, N. W.: Geologic investigations in western Kansas, with special reference to oil and gas possibilities; structure and limits of the Kansas salt beds. Kansas Geol. Surv., Bull. 11: 90–95, 1926.

[9] Twenhofel, W. H.: Geology and invertebrate paleontology of the Comancheon and "Dakota" formations of Kansas. Kansas Geol. Surv., Bull. 9: 30–34, 1924.

probably tap the Dakota, but most of the water may come from the overlying Emma Creek formation. The sandstones of the Dakota group appear to yield adequate supplies of potable water for domestic and stock use.

Tertiary Rocks.

General Features.—The term McPherson Equus beds was used by previous investigators to include all of the unconsolidated deposits in Harvey and McPherson Counties, and all of these beds were held to be of Pleistocene age. The present investigation has revealed, however, that although a part of these deposits is Pleistocene in age, a large part appears to be Pliocene in age. It is here proposed to remove the Pliocene beds from the McPherson Equus beds of Haworth and Beede and assign to them the name Emma Creek formation—from exposures along Emma Creek in southeastern McPherson County. The McPherson formation (restricted) is retained to include only the fluvial deposits of Pleistocene age.

The Emma Creek formation and the McPherson formation (restricted) are easily distinguishable in the field on the basis of lithology and topographic position. The sands and gravels of the Emma Creek were derived from the Cretaceous and Permian rocks adjacent to the north and east. They consist largely of quartz grains but also contain many grains and pebbles of the harder sandstones and concretions of the Dakota group, pebbles and cobbles of Permian chert, and of Cretaceous and Permian shale. The McPherson formation (restricted) comprises glacial outwash and contains grains of feldspar, acid and basic igneous rocks, and red quartzite, whereas none of these constituents is found in the Emma Creek formation. The Ogallala formation, which interfingers with the Emma Creek to the southwest, consists dominantly of pebbles and grains of igneous rock, and contains only very small amounts of chert and materials derived from the Dakota group. The sands and gravels of the Emma Creek formation are typically red-brown in color, whereas those of the McPherson formation are gray to gray-buff in color. Locally the

sands and gravels of the Emma Creek are cemented to a friable sandstone or conglomerate by calcium carbonate; the McPherson deposits are not cemented with calcium carbonate but locally contain beds in which the grains are coated with manganese. The Ogallala formation is typically indurated by calcium carbonate to a hard "mortar bed" type of rock. Therefore the sands and gravels of the Emma Creek formation are readily distinguishable lithologically from those of the McPherson formation (restricted) and the Ogallala formation.

The clay and silt phases of the Emma Creek formation are massive, well compacted, and contain admixtures of sand and gravel. They are red-brown to brown-buff and gray in color. The silt phase of the McPherson formation is thin bedded or laminated, loosely compacted—each thin bed consisting of well sorted fine sand or silt. These beds are typically tan to yellow-buff in color.

The upper surface of the Emma Creek formation comprises the upland plain except in those localities in which it is overlain by eolian deposits. The McPherson formation (restricted), on the other hand, occurs as a valley deposit, channeled into the Emma Creek formation. An erosional unconformity, with a maximum relief of about 200 feet, separates the two formations, as shown in figure 3. The upper surface of the McPherson deposits merges with the surface of the Arkansas alluvial plain in the southern part of the area, whereas the Emma Creek formation caps the eastern bluff of this alluvial plain.

The Emma Creek formation ranges in known thickness from 10 to 180 feet. The maximum thickness of the Emma Creek was accumulated in the depressional area caused by the solution in the salt beds of the Wellington formation, where the westward and southwestward flowing streams were met by streams from the west. Here the Emma Creek interfingers with the easternmost beds of the Ogallala formation and thus at least in part is contemporaneous with the Ogallala.

Vertebrate fossils collected by J. C. Frye from exposures near the top of the Emma Creek and from test holes were submitted to Mr. Claude Hibbard, of the University of Kansas. Hibbard

referred the specimens to *Equus* (*Plesippus*) cf. *simplicidens* Cope, and states [10] that the specimens resemble material taken from the upper Pliocene of Clark County, Kansas.

The Emma Creek formation appears to be of middle and upper Pliocene age because it is in part contemporaneous with the Ogallala formation of middle Pliocene, because it contains upper Pliocene fossils near the top of the formation, and because it underlies unconformably beds of Pleistocene age.

Water Supply.—The Emma Creek formation is only a fair water bearer, and is much less productive than the McPherson formation or the alluvium. The content of sand and gravel is low, and except in local channels the materials are fine-grained and poorly sorted. The Emma Creek supplies the City of Galva, and probably supplies at least in part the Cities of Moundridge and Canton. The waters are of fair quality except in places where they have been contaminated by oil-field brines.

Quaternary Rocks.

McPherson Formation (Restricted).

General Features.—In 1897 Haworth and Beede [11] applied the name McPherson Equus beds to include all unconsolidated deposits in Harvey and McPherson Counties, and in 1920 Moore [12] referred to these same beds as the McPherson formation. As described above, a part of this unconsolidated material has been assigned to the Tertiary, and as described below, another part is now known to be of eolian origin. The McPherson formation (restricted) is used in the present report to include only the fluvial deposits of Pleistocene age.

Previous investigators [13] in the area held that the "Equus beds" were deposited by a stream that flowed from the Smoky Hill River to the Arkansas River but were puzzled to account for

[10] Personal communications dated Jan. 13, 1939, and May 19, 1939.

[11] Op. cit., p. 287.

[12] Moore, R. C.: Oil and gas resources of Kansas, Part 2, geology of Kansas. Kansas Geol. Surv., Bull. 6: 93, 1920.

[13] Haworth and Beede: op. cit., pp. 290–295.

the so-called McPherson Ridge that lies across the old channel. In the present investigation the fluvial origin of the deposits was substantiated and it was found that the portion of the "McPherson Ridge" that crosses the old channel is composed of loess that attains a maximum thickness of 110 feet.[14]

The channel deposits of the McPherson formation (restricted) consist mainly of fairly well sorted quartz sands and silts interbedded with beds of fine to coarse gravel and beds of clay. The sands and gravels contain grains of feldspar, chert, igneous rocks of several types, and red quartzite. The channel deposits attain a maximum thickness of 150 feet. These channel deposits appear to have been derived from the north by meltwater from a retreating Kansan glacier that stood across the valley of the Kansas River in northeastern Kansas.[15]

The McPherson formation also includes thin-bedded and laminated silts consisting of locally derived materials deposited under slack-water conditions in small tributary valleys, during the time the main valley was being filled. Such deposits are found in the valleys of Sand Creek, Emma Creek, and Turkey Creek, and attain a maximum thickness of 40 feet.

Water Supply.—In most places the McPherson formation (restricted) contains beds of clean gravel or coarse sand that yield water freely, and are second in productivity only to those of the alluvium. The public water supplies of McPherson, Inman, Buhler, Halstead, and Newton are obtained from this formation. One of the municipal wells at McPherson yield 1,400 gallons a minute and the other 2,000 gallons a minute, with drawdowns of 17 and 27 feet respectively. In the vicinity of Halstead the McPherson waters are of very good quality and have a hardness of less than 150 parts per million. The McPherson waters are much harder near the City of McPherson, and in some places south of McPherson these waters contain appreciable amounts of iron.

[14] Frye, J. C.: Physiographic significance of loess near McPherson, Kansas. A. A. P. G., Bull. 23 (8): 1232–1233, 1939.

[15] Schoewe, W. H.: Evidence for a relocation of the drift border in eastern Kansas. Jour. Geol., 38 (1): 67–74, 1930.

Loess.

General Features.—As shown in Fig. 2, a large part of the area is covered by a mantle of Pleistocene loess, which is actually much larger than shown, as the area mapped includes only those parts in which the loess was found to be three feet thick or more. The loess was found to be 110 feet thick just northwest of McPherson. The area underlain by loess comprises well rounded slopes with a dearth of natural exposures.

The loess consists mainly of silt, but there is considerable range in texture. Most of the loess is reddish-tan in color, but some of it is brick red and some is yellowish-tan. Nodules of calcium carbonate commonly occur disseminated evenly in the loess or concentrated in well defined bands. Locally, a thin bed of volcanic ash occurs at or near the base of the loess.

There does not appear to be sufficient evidence to warrant the correlation of this loess with similar deposits of loess in western Kansas described by Elias [16] or with loess in Nebraska described by Lugn [17] and correlated with the Loveland and Peorian of Iowa. Volcanic ash is found at the base of the Loveland loess in Nebraska [18] and also at the base of the loess in this area, but the distinct red color of the loveland of Nebraska appears to be lacking here.

Water Supply.—The loess is relatively impervious and yields practically no water to wells. Where thick, it prevents or retards rainfall from reaching underlying formations.

Alluvium.

General Features.—Alluvial deposits of the Arkansas River underlie an area 7 to 10 miles wide bordering the river, the greatest width occurring on the northeast side. The alluvium consists of unconsolidated gravel, sand, silt, and clay. Its maximum thickness is approximately 300 feet, and occurs 3 to 4 miles

[16] Elias, M. K.: The geology of Wallace county, Kansas. Kansas Geol. Surv., Bull. 18: 163–180, 1931.

[17] Lugn, A. L.: The Pleistocene geology of Nebraska. Nebraska Geol. Surv., Bull. 10, 2nd ser.: 128–168, 1935.

[18] Lugn, A. L.: op. cit., p. 132.

southwest of Patterson. The deposits thin down stream to about 80 feet in the vicinity of Wichita, and upstream to somewhat more than 100 feet near Hutchinson. The alluvium thins rapidly to the northeast and southwest from the Arkansas River. It thickens, however, where the filled Pleistocene valley of the Arkansas is encountered. This filled valley roughly parallels Kisiwa Creek, and the maximum known thickness of its fill, 275 feet, occurs southeast of Burrton. Forty to fifty per cent of this material is composed of sand and gravel. The gravel for the most part is moderately well sorted and contains pebbles ranging up to 3 inches in diameter. The rock types represented in the sands and gravels include granite of several varieties, feldspar, pegmatite, aphanitic igneous rocks, and quartz. Clay balls and caliche pebbles from the Tertiary to the west are also locally abundant, particularly in the lower part. These sands and gravels range in color from tan-brown to dove-gray. Clay, silt, and sandy silt make up the remainder of the thickness. This material is massive and generally well enough compacted to allow open-hole cable-tool drilling. In color it includes beds of tan-brown, tan, gray, blue-gray, black, and rarely ash gray.

The uppermost part of the alluvium has yielded Recent vertebrate fossils. Tertiary pebbles from test holes at considerable depth in the alluvium indicate that the older alluvium is post-Tertiary, and it is believed to be Pleistocene. However, it is difficult to determine the exact contact between the Pleistocene and the Recent alluvium.

Water Supply.—The alluvium of the Arkansas Valley is the most productive water bearer in the area. Although the alluvium is more than 250 feet thick in some places, in general the most productive gravels and sands occur within a depth of 75 to 100 feet. The coefficients of permeability of typical alluvial materials, as determined by both field and laboratory methods, range up to more than 5,000. The yields from properly constructed wells range up to more than 2,000 gallons a minute, and the specific capacities of such wells range from about 25 to 140 gallons a minute per foot of drawdown. The alluvium supplies the Cities of Wichita, Hutchinson, Burrton, Sedgwick, and Valley Center.

The water in the alluvium is of good quality except in a belt about a mile wide on both sides of the Arkansas River, in which the water is hard and saline, and in places where it has been contaminated by oil-field brines.

Sand Dunes.

General Features.—Sand dunes are the most prominent topographic features in the area. The most extensive area of dunes occurs in an east-west belt, about five miles wide, that extends from points south of Medora and Buhler eastward to the Little Arkansas River. This dune area is the eastern continuation of the extensive dune area to the north and northwest of Hutchinson. These dunes developed on a ridge composed of red sandy silt, and gray clay and sand of the Emma Creek formation. The underlying materials are exposed in isolated blowouts and cuts.

In the Hutchinson area, Smith [19] has found evidence, consisting primarily of buried soil zones and variations of bedding, that indicates at least three, and probably four or more, cycles in the development of these dunes. It is believed that dune building in this area was initiated in the Pleistocene. This is indicated by the multiple soil zones that have been noted, and the thick soil that now locally overlies certain dunes. The facts that the bedding in the older cycles is quite different from the bedding in the more recent cycles, and that the texture of the sand is somewhat different, seem to indicate that climatic conditions and wind direction during late Pleistocene were different from those during the Recent. The maximum thickness attained by dune sand in this area is approximately 100 feet.

As shown on Fig. 2, there are several small areas of dunes on the alluvial plain, between the Arkansas River and Kisiwa Creek. These dunes have a general west-northwest trend, parallel to both the Arkansas River and Kisiwa Creek, and somewhat closer to the latter. For the most part they are quite low, with a soil cover thick enough to permit normal agriculture. The maximum thickness of sand encountered in this area was 30 feet.

[19] Smith, H. T. U.: Quaternary Dune building in central Kansas. G. S. A. Proc. 1937, p. 115, 1938.

Water Supply.—The dune sand is well sorted and quite porous, and where free of soil or vegetation, is able to take up considerable water from rainfall. However, it is very fine-grained and therefore will not yield sand-free water in appreciable quantities. A large part of the recharge received by the dunes migrates into underlying and adjacent formations, where it becomes available for recovery by wells. The waters in the dune sand are quite soft.

TEST DRILLING.

A total of about 160 test wells were put down during the investigation. Nineteen cable-tool test wells were put down in the Arkansas River Valley by the City, under the supervision of the Geological Survey, in order to determine the thickness and character of the water-bearing beds, quality of water at different depths, and depth to bedrock (shale). Samples of material were collected for determining mechanical analyses and permeabilities, and by the use of a specially designed pneumatic packer, samples of water were obtained from each water-bearing stratum. From one to three 1¼-inch screened well points attached to 1¼-inch pipes were left in each hole to serve as observation wells. It was thus possible to compare the heads of the waters from deep, intermediate, and shallow sources. The logs of these test wells were plotted to show the approximate mechanical analyses of the sediments.

This test drilling revealed that the thickest and most productive sands and gravels and the water of best average quality were obtainable in materials that occupy a former channel of the Arkansas River that lies several miles north of the present channel. This drilling was later supplemented by 40 rotary test wells put down by the consulting engineers for the City in order to select final well sites for the new Wichita water supply.

Forty additional rotary test holes were put down by the Geological Survey to determine the thickness and character of the McPherson formation and the shape and course of the old stream channel in which this formation was deposited. The old channel was traced south from the Smoky Hill River and was found to pass just west of McPherson. At a point near Buhler, the chan-

nel swings east-southeast, and a short distance south of Halstead it merges with the old channel of the Arkansas River. A section across the channel north of McPherson based upon 15 rotary test holes and a section from Inman to Goessel based upon 13 rotary test holes are shown in Fig. 3. An east-west section west of

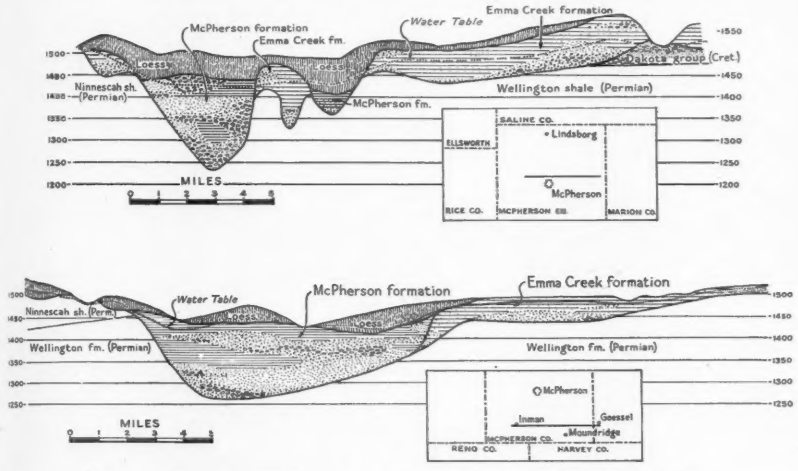

FIG. 3. East-west sections across the "Equus beds" area based upon rotary test holes.

Newton and a section extending from a point six miles south of Haven, Reno County, northeast to a point one mile south of Goessel, Marion County, are shown in Fig. 4.

About 60 driven wells were put down, in part to aid in the construction of the water-table contour map, but mainly to study both the lateral and vertical migrations of oil-field brines. Much of the brine produced with oil has been disposed of in so-called evaporation ponds. Actually most of the brine is believed to escape by seepage into the underlying pervious materials, and has caused serious pollution in some places. The wells were driven at selected points on the downstream sides of disposal ponds, and water samples were taken at vertical intervals of 5 feet.

FIG. 4. Sections across the "Equus beds" area based upon cable-tool and rotary test holes (indicated by vertical lines).

It was found that the brine, being considerably heavier than fresh water, sinks with surprisingly little diffusion or dilution until it encounters an impervious stratum. It then flows laterally in a thin layer on top of this impervious stratum. At one locality a layer of brine 200 feet from its source had suffered practically no dilution. At another locality the dilution in 750 feet was about 1 of salt water to 50 of fresh water.

SHAPE OF THE WATER TABLE AND MOVEMENT OF WATER.

A detailed contour map of the water table was constructed, based upon water-level measurements in several hundred wells. The altitudes of the measuring points and of the water surfaces in the major streams and lakes were determined mainly by instrumental levels, but in the northern part of the area, in part by barometric levels. A simplified version of this map, showing only the 10-foot contours, is shown in Fig. 5.

In the Arkansas Valley, the direction of movement of the ground water is seen to be essentially parallel to the general trend of the valley, except near the margins of the valley. At the time the measurements were made, the surface of the water in the Arkansas River stood at the level of the water table, as shown by the contours, and therefore that stream was neither losing water into nor gaining water from the ground-water reservoir. However, under conditions of low ground-water levels in this area and abundant or excessive precipitation in the upper Arkansas Valley, the stream becomes influent; that is, it loses water into the ground. Conversely, when ground-water levels in this area are high, and precipitation is low in upstream areas, the stream becomes effluent; that is, it gains water from the ground-water reservoir. The average gradient of the water table in the Arkansas Valley is about 5¼ feet per mile. This equilibrium between the water table and the surface of the Arkansas River has an important bearing on the quality of the ground-water in the valley. The Arkansas River water carries considerable salt, and owing to the fact that the stream is influent part of the time, the ground waters in a narrow belt parallel to the river are saline. If the

FIG. 4. Sections across the "Equus beds" area based upon cable-tool and rotary test holes (indicated by vertical lines).

HARVEY CO.
SEDGWICK CO.

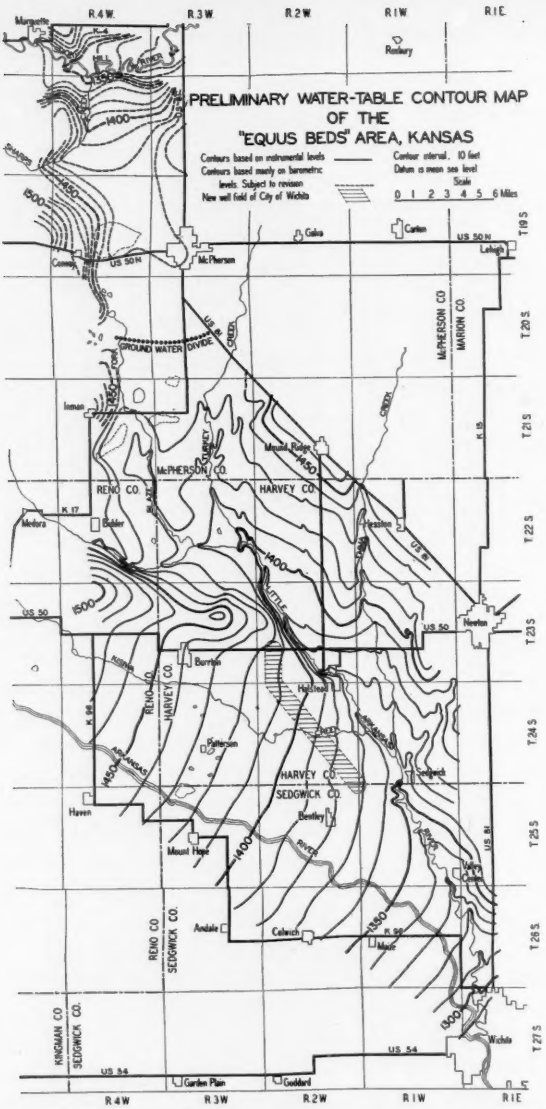

FIG. 5. Map of the "Equus beds" area, Kansas, showing contours of the water table, July and August, 1938, and the location of the new Wichita well field.

Arkansas River were influent at all times, it is likely that saline ground water would occur in a much larger part of the valley.

The contour map also shows that the water surface in the Little Arkansas River and in most of its perennial tributaries stands considerably below the general level of the water table and that except during floods these streams continually gain water from the underground reservoirs. Thus, the Little Arkansas River carries the ground-water discharge of a large part of the area. The average of the mean daily discharge of the Little Arkansas River exclusive of high stages amounts to about 24 million gallons a day.

It will be seen that the average gradients east of the Little Arkansas River and at the north end of the area are steeper than those in the Arkansas Valley. However, this does not necessarily indicate greater velocity of ground-water movement. The steep gradients occur mostly in areas underlain by less permeable materials, such as the Permian shales or the Emma Creek formation.

The ground-water ridge north of Burrton coincides with the sand dune area shown in Fig. 2, and appears to result from the effective recharge from rainfall. The highest crests may represent perched water, but throughout the sand-dune area the true water table is known to stand quite high. The recharge received by the sand hills contributes to the flow of the Little Arkansas River north and east of the sand hills. South of the sand hills this water contributes materially to the underground flow in the Arkansas Valley.

It is the common belief of well drillers and others in the "Equus beds" area that most of the water in the McPherson formation comes from the Smoky Hill River, and flows south past McPherson toward the Arkansas Valley. On the contrary, as shown by the contour map, there is a definite ground-water divide southwest of McPherson, north of which the ground-water in the McPherson formation flows north toward the Smoky Hill River. The ground-water divide indicated in Fig. 5 is in the middle of a saddle-shaped divide in permeable material. East

and west of this saddle, the divide is in relatively impervious material, is sharper, and coincides more closely with the surface divide.

The water table is nearly flat in the vicinity of the ground-water divide, owing to the thick deposit of relatively impervious loess that covers the McPherson formation and prevents the downward percolation of the rain.

WATER-LEVEL FLUCTUATIONS.

Periodic water-level measurements are being made in about 154 observation wells in the area. A part of them are observed weekly and part are observed only monthly. Seven automatic water-stage recorders have been maintained on wells. Descriptions of most of the observation wells and periodic water-level measurements have been published in the annual water-level reports of the U. S. Geological Survey.[20] The period of record is as yet relatively short, and there has been opportunity for only a cursory study of the measurements made to date.

As would be expected, the fluctuations of maximum amplitude occur in wells in shale. This does not indicate that the shales are highly receptive of recharge, but indicates that, owing to the low specific yield of shale, a small amount of recharge will produce a large rise in water level.

In the more permeable materials of high specific yield the response to rainfall ranges widely according to the nature of the soil or other surficial material. The greatest rises in water level in response to rainfall are found in wells in the porous sand hills. The wells showing the least response to precipitation are those south and west of McPherson, where the thick blanket of loess covers the sands and gravels of the McPherson formation. Here the water table stands 60 to 80 feet below the land surface. The fact that the water level in Lake Inman is perched about 16 feet above the water table, indicates that the loess in that locality is quite impervious.

[20] Water levels and artesian pressure in observation wells in the United States in 1937. U. S. Geol. Surv. W. S. P. 840: 101–107, 1938; W. S. P. 845: 116–133. 1939.

In the Arkansas Valley the water table stands only 10 to 15 feet below the land surface over large areas. The soil is very sandy and the water levels respond quickly to rainfall. The average annual precipitation at Wichita is 31 inches, and of this amount it is believed that as much as 15 per cent probably reaches the water table. During May and June, 1938, when the precipitation was considerably above normal, nearly half the water that fell appeared as recharge. During periods of low rainfall, however, much of the water that falls never gets below the soil zone and there may be no recharge.

There is considerable ground-water discharge in the Arkansas Valley, most of which is through transpiration by groves of trees along the Arkansas and Little Arkansas Rivers, and locally by other plants or crops. Considerable ground water is also discharged into the Little Arkansas River, as indicated by the contour map. The principal artificial discharge is through municipal and industrial wells at Wichita, and through municipal wells at smaller communities in the valley. Very little water is pumped for irrigation in the valley, except locally in times of drought.

WICHITA'S NEW GROUND-WATER SUPPLY.

The present water supply of the city of Wichita is pumped from shallow wells in the alluvium at the confluence of the Arkansas and Little Arkansas Rivers. The average daily consumption is 10 to 12 million gallons, and during hot, dry summers, peak pumpage has ranged as high as 21 million gallons a day. Although adequate in quantity, the water is of very poor quality. The hardness is in excess of 450 parts per million, much of which is permanent hardness, and the chloride content is about 600 parts per million.

As a result of the present investigation, a new supply has been developed in the area (Fig. 4). Twenty-five permanent wells have been drilled and tested and a pipe-line and other works are now under construction for conducting the water to the City. The new supply is expected to be put into operation by July, 1940.

The following information concerning the new wells was sup-

plied by Mr. R. E. Lawrence, Black & Veatch, Consulting Engineers. The wells were drilled to a minimum diameter at the bottom of 30 inches. The well screens and blank casings have an inside diameter of 18 inches. All blank casing and 23 of the 25 screens are made of no. 3 gauge pure ingot iron. Two of the screens, however, are made of cast iron. The annular spaces around the casing and screen are filled entirely to the top with screened gravel. A few of the shallow wells were excavated by means of an orange-peel bucket, but the deeper wells were drilled by the rotary method. Other pertinent data in regard to these wells are given in Table 2.

TABLE 2.

RECORDS OF NEW WICHITA PUBLIC-SUPPLY WELLS.
(Courtesy Black and Veatch, Consulting Engineers.)

No.	Depth (feet)	Total Screen Length (feet)	Depth to Water (feet)	Yield (gallons a minute)	Drawdown (feet) [1]	Specific Capacity (gallons a minute per foot of drawdown)
1	228	60	20.6	1,560	60.9	25.6
2	234	60	20.3	1,400	64.0	21.9
3	236	65	25.2	2,000	62.6	31.9
4	237	60	25.2	910	63.8	14.3
5	238	65	20.4	1,420	66.1	21.5
6	258	60	24.2	2,040	64.6	31.6
7	124	60	12.0	2,030	14.4	141.0
8	259	65	20.1	1,570	73.2	21.4
9	247	65	13.5	2,010	47.7	42.1
10	263	65	14.4	1,800	73.9	24.4
11	228	55	9.7	1,980	35.2	56.2
12	239	60	15.2	1,960	45.3	43.3
13	244	60	11.2	2,010	42.3	47.5
14	103	35	10.7	1,570	28.4	55.3
15	195	55	14.9	2,030	37.4	54.3
16	196	60	13.4	2,000	49.4	40.5
17	187	50	9.3	2,010	51.2	39.3
18	156	40	11.1	1,860	43.7	42.6
19	147	—	14.1	1,280	40.0	32.0
20	245	60	13.2	2,010	60.1	33.4
21	80	30	12.6	1,870	20.9	89.4
22	82	30	14.3	710	20.8	34.1
23	206	55	13.5	1,870	56.1	33.3
24	97.5	30	13.7	1,480	26.1	56.7
25	188	55	10.5	1,980	43.2	45.8

[1] After pumping 36 hours.

In order to prevent local overdevelopment, the final rates of pumping are to be adjusted to range from 500 gallons a minute for the weaker wells to not more than 1,000 gallons a minute for the best wells.

The City's consulting engineers estimate that the hardness of the new water should not exceed 180 parts per million (chiefly temporary hardness) and that the chloride should not exceed 35 parts. Treatment facilities are being provided for removing from the water a slight excess of iron. They also estimate that by 1960 the City may require an average of 20 million gallons daily, with possible daily peaks of as much as 30 million gallons.

The location of the new well field (Fig. 5) was the result of a compromise in order to secure the maximum quantity of water of the best possible quality, and with the least danger of contamination by salt water. Owing to the high salinity of the ground-waters in a narrow belt parallel to the Arkansas River, it was necessary to stay as far from this river as possible. It was also necessary to keep as far as possible from the Burrton oil field, just west of Burrton, in order to lessen the danger of contamination from oil field brines.

It is estimated that the natural ground-water flow across the well field, under the natural hydraulic gradient with no pumpage, is about 5 million gallons daily. Thus since the remainder of the supply must be pumped largely from storage and replenished by rainfall, it was necessary that the pumpage be distributed over as much area as possible in order to receive the benefit of as much recharge as possible and to prevent excessive withdrawal from storage locally. In order to satisfy this requirement the 25 supply wells were distributed along a belt more than 9 miles long, with a minimum distance between wells of one-half mile.

With the final selection of the new well field were embodied several important limiting conditions, as follows: (1) That every effort should be made to eliminate the disposal of brine into surficial materials in the Burrton area in favor of deep disposal wells; (2) That in order to safeguard the water from contamination, a series of outpost wells should be put down just downstream from

the Burrton oil field so that samples of water from different depths may be analyzed periodically in order to detect in advance any considerable body of brine that may be migrating toward the well field; (3) That the old well field at Wichita should be maintained in good working order to serve as an emergency supply if and when needed; (4) That new water-table contour maps should be constructed periodically to show whether or not the safe yield is being exceeded; (5) That if at any time in the future it appears that the safe yield is being exceeded, consideration should be given to extending the well field north and southeast, and consideration should also be given to the possibility of supplementing recharge from rainfall by spreading water diverted from the Little Arkansas River.

Through the efforts of the Kansas State Board of Health, considerable progress has been made in bettering conditions in the Burrton oil field, and at present almost all of the brine is being conducted to deep disposal wells. A line of outpost wells has been drilled along a northeast line that passes through Burrton. Some of the wells tap the deepest sands just above the shale; others tap beds at intermediate depths; and some tap shallow sands. Periodic analyses of waters from these wells to date indicate that no considerable quantity of brine appears to have reached this line. Should subsequent analyses indicate otherwise, a second line of outpost wells will be drilled one mile to the southeast, in order to determine the velocity of movement and rate of dilution of the brine. It is believed that recharge from rainfall will cause considerable dilution during the long time required for migration of the brine.

As indicated above by condition no. 4, the studies in regard to the safe yield of the well field will be continued as long as possible. An unusual opportunity is thus afforded for completing a detailed quantitative study. The continuing study would be impracticable without the knowledge of static conditions that prevailed prior to the time pumping begins in the new well field.

U. S. GEOLOGICAL SURVEY,
LAWRENCE, KANSAS,
April 16, 1940.

ABUNDANCE AND SIGNIFICANCE OF CRISTOBALITE IN BENTONITES AND FULLER'S EARTHS.

JOHN W. GRUNER.

ABSTRACT.

Cristobalite is a common constituent in bentonitic clays. It can be detected by the x-ray powder method. It probably has no detrimental influence in such cases where the clay is used for fuller's earth. The origin of the cristobalite is puzzling, and no hypothesis that can be advanced is satisfactory.

INTRODUCTION.

GEOLOGISTS have become used to the idea that authogenic feldspar probably forms near room temperature and authogenic tourmaline may have a similar history, but few geologists would suspect cristobalite in sediments unless these rocks had been subjected to heating. It is true that Beljankin and Petrov[1] claim that "cristobalite is not rare in sedimentary formations, and it has been listed many times as associated with such typically hydrochemical minerals as opal or montmorillonite."

They do not give a single reference to accompany this statement and search through the literature has been unsuccessful on the writer's part. It is probable, therefore, that they refer to the all Russian literature. Von Moos[2] in an article on unconsolidated rocks includes a diagram in which cristobalite is given a place among the finest grained fractions below a diameter of 2 microns. He gives no other information on the subject. It is possible that von Moos as well as the Russian authors have in mind the work of Levin and Ott,[3] who report cristobalite of high and low temperature modifications in natural opals. Vasileff and

[1] Beljankin, D. S., and Petrov, V. P.: Occurrence of cristobalite in sedimentary rock. Am. Min., 23: 153, 1938.

[2] Von Moos, A.: Unverfestigte Sedimente und Erdbaumechanik. Geol. Rundschau, vol. 29, 1938.

[3] Levin, I., and Ott, E.: X-ray study of opals, silica glass and silica gel. Zeit. Krist., 85: 305–318, 1933.

Vasilevsky,[4] who made similar investigations claim to have found α cristobalite not only in massive opal, but also in diatomaceous earths and tripoli. Their illustrations are not so convincing, however, and in the light of x-ray analyses made by the writer on diatomaceous earths and tripoli, the very few indistinct lines in the photographs may not indicate a truly crystalline compound because similar lines have been obtained by several x-ray workers in silica glasses. Lately the writer has found α cristobalite, however, in large amounts in bentonite and has described its identification in a preliminary paper.[5] Since then more occurrences have been discovered which will be mentioned below.

IDENTIFICATION OF CRISTOBALITE.

It is doubtful whether any of the cristobalite described could be detected by any other means than the x-ray powder method. The particles are comparable in fineness with the clayey or bentonitic material in which they occur. Under the microscope individual particles are hardly observable, only aggregates that are partly made up of cristobalite, montmorillonite, and perhaps quartz or mica. As a matter of fact several of the samples in which the cristobalite occurs in relatively large amounts were examined and described by competent petrographers a number of times without the detection of the mineral.

With x-rays no trouble is experienced in identifying the pattern of the mineral provided the percentage of it is not too small. It is probable that even amounts as low as 5 per cent could be detected by the most prominent line of α cristobalite d = 4.03 Å. For details of the powder photograph the reader is referred to the paper mentioned above.[6]

There are at least six diagnostic lines. Fortunately these lines cannot be mistaken for those of minerals that are most likely to occur with cristobalite, such as quartz, montmorillonite (or beidellite), feldspars, muscovite, kaolinite, or other layer minerals.

An idea of the quantity of the mineral can be gained by the

[4] Jour. Phys. Chem. (U.S.S.R.), 7: 918, 1936. All in Russian.

[5] Gruner, J. W.: Cristobalite in bentonite. Am. Min., vol. 25, in press.

[6] Gruner, J. W.: *op. cit.*

intensity of the lines as compared with patterns of other minerals present. Montmorillonite, however, is apt to be underestimated in such comparisons as it gives about the most poorly defined and least intense pattern of silicates. In such cases a quantitative analysis of SiO_2 and Al_2O_3 might be made, as described by the author in the American Mineralogist. The excess of SiO_2 over that needed for montmorillonite would give the approximate percentage of cristobalite if these minerals were the only ones present.

DISTRIBUTION AND ABUNDANCE.

So far cristobalite has been discovered in bentonites and fuller's earths from Montana, Wyoming, Colorado, Texas, Missouri, and Illinois.

The ages of most of these clays are known. The samples are described below:

(1) Near Miles City, Montana. The material is grayish white and compact. It breaks with conchoidal fracture. When put into water the fragments do not immediately slake and swell, but become very slippery and stick to the vessel. Swelling is very gradual. The powder photograph shows much montmorillonite, perhaps 10 to 15 per cent cristobalite, and about 10 to 15 per cent quartz. The latter is also very fine grained like the other minerals. A very slight amount of gritty material in the sample proved to be angular grains of feldspar. A photograph of the outcrop shows a dip of the formation of 30 to 40 degrees. Its age is unknown to the writer.

(2) Near Gillette, Wyoming. This material has been described in detail, including its analysis.[7] Its physical texture and behavior are similar to material No. 1. Since it contains only montmorillonite and cristobalite, according to x-rays, and 68.7 per cent SiO_2, it must contain about 30 to 40 per cent cristobalite. This material is used commercially at present. Its age is not known, but if it comes from the same horizon as the bentonite from Belle Fourche, South Dakota, it is a member of the Graneros shale and Upper Cretaceous. The Belle Fourche samples do not seem to contain cristobalite.

[7] Gruner, J. W.: *op. cit.*

(3) Near Sheridan, Wyoming. This is a good bentonite that swells rapidly. It is cream colored and has conchoidal fracture. The x-ray photograph shows only montmorillonite and cristobalite. The latter probably exceeds 30 per cent of the total material.

(4) Near Casper, Wyoming. The description of this bentonite is like No. 3, but it also contains very finely divided quartz. The intensity of the lines suggests more than 25 per cent cristobalite.

(5) Custer County, Colorado. This material was given to the author by a commercial firm that intends to use it for medical purposes. It is said to possess special properties including radioactivity. The sample is white and chalky in appearance. In water it feels soapy but it does not disperse unless it is ground up first and stirred for a long time. Some of it will stay in suspension then indefinitely. This suspended material as well as the bulk sample show the same relative amounts of cristobalite and montmorillonite. The percentage of cristobalite is higher than in the other samples, probably as much as 40 per cent. The percentage of SiO_2 is supposed to be around 70 per cent.

(6) Near College Station, Texas. The bentonite is one of three samples from the Catahoula formation (Miocene). It does not swell in water. It has a conchoidal fracture and light gray color, which is probably due to extremely finely divided iron sulphide, some of which is visible with the hand lens. The sample contains 76.01 per cent SiO_2. Cristobalite and montmorillonite are the only detectable constituents besides the iron sulphide. The cristobalite probably makes up over 40 per cent of the sample.

(7) Olmsted, Illinois. This material is used for fuller's earth and belongs to the Porters Creek formation of Eocene age. Its properties and chemical composition have been described in detail by Grim, Bray and Bradley [8] under number 3 in their paper. Although they noticed the high SiO_2 content in the material [9] they

[8] Grim, R. E., Bray, R. H., and Bradley, W. F.: The constitution of bond clays and its influence on bonding properties. Trans. Am. Foundrymen's Assoc., 7: 211–228.

[9] *Op. cit.*, p. 217.

did not discover the cause of it, but thought that it might be due to amorphous silica. The sample contains not only montmorillonite and cristobalite, but small amounts of kaolinite and quartz. Cristobalite must be present in excess of 25 per cent, judging by its x-ray photograph.

(8) Ellis Farm, Scott County, Missouri, Sec. 25, T. 29 N., R. 14 E. This sample and Nos. 9, 10 and 11 were kindly furnished by Dr. V. T. Allen. He has described the material in detail, especially optically.[10] The four samples submitted do not swell readily but have a tendency to break up into smaller fragments when placed in water. An analysis made by the writer of No. 8 gives 64.87 per cent SiO_2. The x-ray photograph of the untreated material shows about 10 to 15 per cent of very fine-grained quartz besides large amounts of montmorillonite and cristobalite. Material that was centrifuged for 3 minutes at 1200 g. showed no quartz in the portion that stayed in suspension under these conditions, and the lines of cristobalite and montmorillonite were as prominent as before centrifuging.

(9) Avert, Missouri, Sec. 3, T. 26 N., R. 11 W. This locality is about 17 miles southwest of that of No. 8. The behavior of the sample is in every respect like that of No. 9.

(10) Ardeola, Missouri. This sample also resembles No. 8 closely, but it contains no detectable quartz and the proportion of cristobalite seems to be very high possibly 40 to 50 per cent.

(11) Stoddard County, Missouri, Sec. 10, T. 26 N., R. 11 E. This clay shows only a little cristobalite besides quartz and montmorillonite. The analysis supplied by Dr. H. A. Buehler shows 62.80 per cent SiO_2, and 19.37 per cent Al_2O_3.

(12) "Shale" pebbles in drift found northwest of Fergus Falls, Minnesota. This specimen was collected by Mr. Ernest Berg, who asked the writer to make an x-ray analysis a number of years ago. It contains a large amount of cristobalite besides about 5 to 10 per cent quartz. The specimen is not available any more.

[10] Allen, V. T.: Petrography and origin of fuller's earth, Southeastern Missouri. ECON. GEOL., 29: 590–599, 1934.

A number of volcanic ash specimens were x-rayed but in none of them was anything discovered resembling cristobalite. It was already mentioned that no cristobalite was found in three samples of diatomaceous earths. About a dozen bentonitic clays from various localities and ages, beginning with the Ordovician Decorah shale, were also examined for cristobalite besides the ones in which it was found. It may not be justified to draw conclusions with regard to the distribution of the mineral on the basis of these 12 occurrences, but there is no doubt that cristobalite will be found in many other places when investigators begin to look for it.

EFFECT OF CRISTOBALITE ON THE QUALITY OF FULLER'S EARTHS.

So far nothing is known on the behavior of cristobalite with regard to base exchange and adsorption properties. It is certain from the present study that all of the cristobalite is in an extremely finely divided state. The x-ray photographs indicate that most of the mineral, if not all, is in grains smaller than 2 microns. Also, the ratio of cristobalite to montmorillonite seems to remain the same in suspensions subjected to centrifuging as in untreated samples. This means that the surface of the grains is relatively very large and comparable to that of montmorillonite. Also, the structure of cristobalite[11] is of such a nature that more "loose" bonds exist on the surface of a minute grain of it than on a corresponding grain of kaolinite, mica, or even montmorillonite, provided the structure of the latter mineral as proposed is correct. Cristobalite lacks of course the property of absorbing water and swelling, which makes montmorillonite so unique among structures.

It might be asked why cristobalite might be different from quartz in its behavior in fuller's earth if "loose" bonds have anything to do with it as it has no more of them than quartz. In the first place it is doubtful that quartz ever occurs in grain sizes smaller than about 0.1 micron, according to Grim, Bray and

[11] See for example: Bragg, W. L.: Atomic structure of minerals. Cornell Univ. Press, 1937, p. 90.

Bradley [12] and Nagelschmidt.[13] Cristobalite does as far as could be ascertained by the widths of the lines in the powder photographs. Secondly, cristobalite is of less density and more open in structure than quartz. It is probable that in this respect it resembles somewhat zeolites. Substitutions around the margins of grains may be possible. Also absorption of H_2O and other molecules may play a part. There is really no reason why this mineral should not have as good fuller's earth properties as attapulgite and illite,[14] both evidently mica-like minerals of exceedingly fine grain size.

The presence of cristobalite in the clays mentioned should not, therefore, have a deteriorating effect on them as long as they are not used for their property of swelling.

ORIGIN OF CRISTOBALITE.

On first thought one is inclined to connect the origin of cristobalite in the bentonitic clays directly with the origin of the volcanic ash of the clays. α cristobalite seems to have been synthetized at temperatures as low as 180° to 228° C. by Chrustschoff.[15] There is no indication that it can form at lower temperatures. On the other hand, all natural occurrences seem to point to considerably higher temperatures especially since much of the mineral formed originally as β cristobalite in volcanic rocks. If we assume that cristobalite in the bentonites formed at elevated temperatures it must have originated before it issued from the volcanic vents as stated in the author's earlier paper.[16] An argument contrary to this hypothesis is the fact that three samples of volcanic ash that were x-rayed contained no crystalline material. These samples were truly amorphous in character.

Is cristobalite, then, a decomposition product of originally glassy

[12] *Op. cit.*, p. 215.

[13] Nagelschmidt, G.: The identification of minerals in soil colloids. Jour. Agricult. Sci., 29: 489, 1939.

[14] Grim, R. E.: Properties of clay. In "Recent marine sediments," A. A. P. G., Tulsa, 1939, p. 469.

[15] Chrustschoff, K.: Abstract Neues Jahrbuch, vol. 1897, Bd. I, p. 240.

[16] *Op. cit.*, in press.

volcanic ash as is montmorillonite in the bentonites? If it is, it probably is only an intermediate stage in the complete decomposition for it appears that quartz is the final product, for as the amount of cristobalite decreases quartz increases and vice versa, as shown by x-ray powder photographs. The change of metastable cristobalite to stable quartz is also indicated by the discovery that bentonites older than the Cretaceous period seem to contain no cristobalite.

If cristobalite were a product of weathering it is not apparent why it should never be encountered anywhere else in the decomposition of rocks. This fact is a good reason for suspecting that neither montmorillonite nor cristobalite form by processes that are operative in ordinary weathering. Many investigators believe that sea water as a medium was important in the formation of montmorillonite. It is difficult, however, to imagine what role sea water could have played in the crystallization of cristobalite.

CONCLUSION.

Examination of numerous bentonites and fuller's earths shows the presence of α cristobalite in appreciable quantities. As much as 40 per cent of the clay may be cristobalite. The powder method of x-ray analysis is the most reliable, if not the only means with which the mineral may be detected. It is always associated with montmorillonite. It appears that with a decrease in cristobalite an increase of quartz takes place, which indicates that the metastable cristobalite inverts to quartz some time in the history of the clay. So far no cristobalite has been found in clays older than the Cretaceous.

The presence of the mineral seems to have no detrimental effect on the properties of fuller's earth. The extremely fine grain of the cristobalite may offer just as good an adsorbing surface as montmorillonite it is thought. The origin of this type of cristobalite is very puzzling.

If it is a product of elevated temperatures it could scarcely have formed anywhere else than in the throat of a volcano. On the other hand, it is difficult to think of it as a weathering product

of volcanic ash for it is never found as a weathering product anywhere else as far as known.

In conclusion the writer wishes to thank Dr. V. T. Allen and Dr. R. E. Grim for supplying him with some of the specimens. A grant from the Graduate School of the University of Minnesota assisted materially in the investigation.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
June 19, 1940.

METHODS OF RECORDING COAL DATA.[1]

GILBERT H. CADY AND CHARLES C. BOLEY.

ABSTRACT.

The Coal Division of the Illinois State Geological Survey employs the Hollerith punched-card system for recording and tabulating data used in the preparation of structural contour maps based on the altitude of key coal beds. By the use of the punched-card method, after data are once recorded accurately, no further checking is necessary, no matter how they may be reorganized or summarized. A similar system is also being used for recording and tabulating the great variety of information on the chemical characteristics of Illinois coals and coal ashes.

THE Coal Division, which is carrying on extensive studies of the structure, distribution, thickness, and resources of the Illinois coal beds, assembles great quantities of factual data in the preparation of structure maps and in the study of analytical information. The clerical labor of assembling these data in a form suitable for study is great. The elasticity of the hand-prepared tabulations is limited, and handwritten or typewritten copies of such data are inflexible in arrangement, expensive and inconvenient to reproduce, and when reproduced are subject to inaccuracies.

HOLLERITH PUNCHED-CARD SYSTEM FOR RECORDING STRUCTURAL DATA.

In conection with the preparation of structure maps it is necessary to tabulate various data such as the character of the datum point, whether it is a mine, type of drill hole, a water well, or an outcrop; its detailed location, and its position in the section within 10 acres; its surface altitude; the depth, thickness, and altitude of the key bed and of one additional commercially important coal bed if present; the name of the operator of the mine or the driller of the well; and the date when the mine was opened or the well

[1] Presented by permission of the Chief, Illinois State Geological Survey, Urbana, Illinois.

sunk. Once such data have been assembled it is important that the information be preserved in such a way that it forms a conveniently accessible and readily usable permanent record. It is also desirable that the data can be readily assembled in tabulated form, either in whole or in part, on any one of various bases. It is practically impossible to achieve such flexibility using data compiled by hand.

The International Business Machine Hollerith punched-card system is well adapted to meet these desirable requirements of accessibility, flexibility, and permanency of record. The junior author is largely responsible for introducing the method to the Survey and for planning the arrangement of the card.

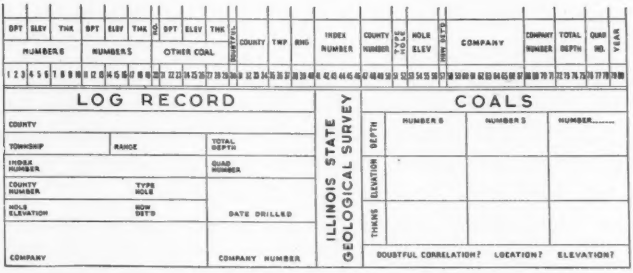

FIG. 1. Log Record Card.

The equipment necessary to operate the system is available in most large cities and University communities. The University of Illinois tabulating office rents the equipment and sublets the machines and the operators' time to various University departments. The Geological Survey uses the equipment relatively little as compared with the time it is employed by the Department of Agriculture, the Physical Plant, and others. It is only because of its large use by various agencies that the equipment is available locally for Survey use.

The "Log Record" card (Fig. 1) is used for the tabulation of location and structure data. This standard card provides 80 vertical columns for the mechanical recording of numbers or

letters, one character to a column. A system of holes is used in the recording, the particular character desired governing the vertical position of the hole or holes in each column. These accurately located holes permit electrical contacts in sorting and tabulating machines, which rearrange, print, or add the information as desired. It is obviously necessary that the cards be standard with respect to dimensions and stock.

All data may be initially recorded by hand or typewriter on the card. This is not always necessary since the cards may be punched from any record that can be interpreted correctly by the operator. The data to be compiled must be systematized so that efficient use is made of the space available. The possible variations in geological data are examined and, if necessary, coded in the most logical manner. The assembling of data for transference to the cards is, of course, done by the geologist, or under his direct supervision.

The card is punched by a machine with a standard typewriter keyboard. The punching produces a card in which the index holes are punched, and, in the case of the machine we use, shows the abbreviated data printed on the upper margin of the card. This printing at the top of the card is not done by all card-punching machines, but undoubtedly is of some convenience in checking and occasional handling of the cards. All machine work, however, depends solely upon the holes.

The order in which the items appear on the upper margin of the card is determined by the mechanical requirements and limitations of the card-punching machine. This order has nothing to do with the order in which data may be reproduced by the tabulating machine.

After the cards have been punched they are handled by the sorting machine, which sorts them mechanically at the rate of 400 cards per minute, one vertical column at a time. The possibility of grouping is essentially unlimited for the data shown on the card. Our cards are grouped first by county and next by county index number, which is a device for classification by township, range, section, and position in the section with respect to any par-

ticular 10-acre tract. Ordinarily for our use the cards need be sorted but once, after which they are filed for use as needed for tabulation. If, however, a grouping is desired by thickness of coal beds, type of hole, drilling operator, or any other criterion, the cards can be rearranged, retabulated, and easily returned to the usual grouping.

Tabulation is performed on the tabulating machine, which will print an original and several carbon copies in a single operation. The items in the table may be arranged irrespective of the order in which they appear on the upper margin of the punched-card, as has been stated above. Considerable variation is possible in the order of the tabulation columns. For the tabulation operation it is necessary to make preliminary electrical connections on a removable switchboard that determines the order in which the items shall appear or eliminates those not desired on a particular tabulation. The "board," being removable, can be set aside for use on a particular job if so desired, in which case it is usually purchased by the user. If this is not done, a board must be reset for each job, a matter of 20 to 60 minutes' work, which is charged as rent for use of the tabulating machine.

The tabulating machine has a printing capacity width of about 14 inches (88 vertical columns) which will take 80 items and allow some room for vertical spacing between columns. It is practically never necessary to reproduce all 80 characters, leaving more room for vertical spacing. The machine will print single or double spaced, and by use of control mechanisms or dummy cards, will triple space or space irregularly, permitting grouping of items in various ways. Across the width of the tabulation sheet, for the machine available to the Survey, letters are restricted to the left-hand 43 of the 88 type-bars available, so that all letters must be shown on the left-hand side of the table if the table is more than 43 spaces wide. Numbers may be shown across the entire width of the table.

The selective mechanism, which permits some information to be printed and withholds other information, is of great convenience. By means of this device it is possible to use the same cards

to produce lists for Survey use upon which all data are shown and to produce lists for public use from which confidential data are excluded.

Tabulations of structural data can be printed to give first copies throughout, if a control switchboard is already set up, at a cost of less than 1/5th cent per item. A compilation of all structural data for Saline, Gallatin, Hamilton, and White counties, representing 854 items, was assembled in a paper-bound 24-page book 10¾ by 14¾ inches and sold at about cost for $1.50. An earlier book of tabulated data for Williamson, Franklin, Jefferson, and some adjacent counties, containing 2800 items, but consisting in part of first and second carbon copies as well as of original sheets, sold for $2.00, about the cost of preparation. Tabulations for individual counties are supplied to oil companies and others as ordered at the rate of 1/5th cent per item, or about 8 cents per page. The cost of reproducing large editions could be considerably reduced by using mineographed copies made from stencils cut by the tabulating machine. Cost data will probably vary considerably from installation to installation depending upon local conditions.

Once the cards are filled out and punched and their accuracy checked by proof-reading of a preliminary tabulation, no further proof-reading is necessary. Typographically correct tabulations for a county or for a group of counties can be run off in a short time if the tabulating machine is available for use. The speed of printing is such that all information contained on a card may be printed at once on a single horizontal line at the rate of 80 cards per minute.

Punched-Card System for Recording Analytical Data.

Since the punched-card system was found useful for recording coal bed structure data, the possibility of its use in recording and tabulating coal analytical data was investigated. The card (Fig. 2) adopted for the purpose contains space for all the items commonly recorded in connection with standard analytical investiga-

tions of coal and coal ash. The great variety of information on record requires the use of one plain and seven differently tinted cards. The tints are an aid to visual selection only; the cards are mechanically separated by means of punched holes.

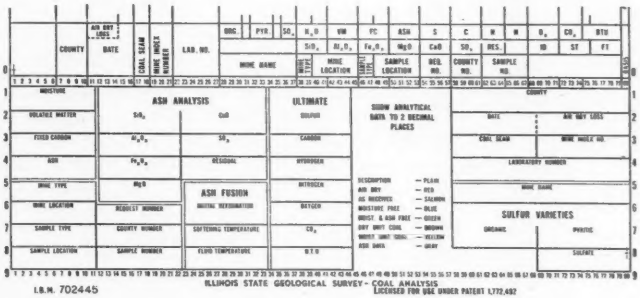

FIG. 2. Coal Analysis Card.

After the cards have been filled out and punched (or punched directly from laboratory records), they are sorted so that all cards descriptive of an individual sample are grouped together, all samples from an individual mine making a larger group, and then all mines of a county are grouped together. This represents the usual order of filing the cards. When a tabulation is desired of any particular kind of information, as for example the items of the proximate analysis or the items of the ultimate analysis, it can be automatically produced by the use of the sorting machine and by setting the switchboard, after which the cards can be automatically rearranged in their preferred filing order.

It is apparent that such a system saves a large amount of time otherwise necessary for handling the complicated analytical data now available for Illinois coal and coal ash. A study of ultimate analyses of Illinois coals for the purpose of reaching some basis for classification, will require elaborate statistical handling of these data, a procedure which would be practically impossible without the mechanical help given by the Hollerith punched-card machine.

The same is true with respect to the study of ash-analysis and ash-fusion relationships. It is expected that this organization of analytical data will simplify the maintenance of a complete list of the Survey's constantly growing coal analysis file. Printer's copy for an analysis bulletin will virtually always be ready.

COAL DIVISION, ILL. GEOL. SURVEY,
URBANA, ILL.,
April 2, 1940.

DISCUSSION AND COMMUNICATIONS

THE NATURE OF THE ORE-FORMING FLUID: A DISCUSSION.

In the supplement to ECONOMIC GEOLOGY for March-April, 1940, Dr. L. C. Graton has a long and important article on the above subject. Its purpose is shown in brief by the following quotation from his abstract:

> Starting from the arguments and conclusions of Fenner, Bowen, Ross, and Schaller in the "Lindgren Volume," this paper undertakes to appraise present knowledge and theory as to the origin, state, composition, migration, and effects of the mobile medium which transports mineral forming materials from the magma and deposits them to form hypogene epigenetic ores.

More specifically, the article combats the idea that mineral matter in general and ore-forming elements in particular depart from the magma in significant amounts in a vapor phase, and favors movement in a liquid solution, formed directly from liquid magma without the intervention of a vapor phase.

The article is an interesting and able presentation of views fundamentally different from those offered in the Lindgren Volume by Bowen and by me. Our views held in common that the medium by which ore-forming elements first escape from the magma is a gas, although we differed from each other in several other respects.

Dr. Graton's article merits careful reading and consideration by those interested in the formation of ores. Such a contribution is to be welcomed. Nevertheless, his arguments have not convinced me that my former views were incorrect. While considering a reply, I received from Dr. Earl Ingerson, of the Geophysical Laboratory, the typescript of an article on the subject that he and Dr.

Morey had written,[1] with a request for comments. This seemed such an excellent paper that at first I was inclined to give up the idea of writing another, but on reflection there seemed to be a number of important matters that Ingerson and Morey had not attempted to cover, and further discussion of Dr. Graton's article appeared desirable.

On p. 207 (footnote) Dr. Graton protests against the manner in which, as he believes, physical chemists have used the term "alkaline" to mean fundamentally different characteristics of a fluid. Possibly there is some basis for this feeling, but hardly to the degree that he implies. Not only as regards "alkaline" but also as regards other physico-chemical terms and conceptions, such as the meaning of "strong acid" and the "critical state" of the magma and its derivatives some confusion is apparent in his paper and affects his arguments. Ingerson and Morey's discussion shows where Dr. Graton has gone astray in some respects in the matter of the "critical state" and this need not be further discussed. They have also contributed certain hitherto unpublished information of value, derived from laboratory investigations, on the ability of vapors, especially water vapor, under high pressure and temperature, to dissolve many substances not themselves volatile. This is welcome information, not only in its bearing upon Dr. Graton's paper but also in relation to the whole question of the possibilities of gaseous transfer.

In regard to the term "strong acid," it should be recognized that a solution may contain a strong acid but need not be strongly acid. Strong acids are those which, in aqueous solution, are greatly ionized. Hydrogen ion is set free, and the amount of ionic hydrogen is indicated by the pH value. HCl is a strong acid, as a drop of this in 100 c.c. of water is almost completely ionized, but the resulting solution is not strongly acid, for it is neutralized by very little alkali. On the other hand, "alkaline," as used by chemists, implies free OH ion. The meaning of this is definite, but a possibility of confusion arises from the fact that to indicate the presence of some compound of an alkali metal

[1] Published in ECON. GEOL., 35: 772–785, 1940.

a term of similar appearance is used, "alkalic" or "alkali-bearing" or "alkali-rich." The confusion, however, does not lie in the conceptions but only in the similarity of the descriptive terms; nevertheless, in geologic literature, instances of misunderstanding are often met. In fact, many geologists apparently believe that alkali-rich magmas, commonly termed alkaline magmas, should have alkaline properties in the chemical sense. In this matter geologists appear to hve been principal contributors to their own misunderstanding, though physical chemists who have written on geologic matters have not been free from fault in a loose usage of terms.

The confusion between alkaline and alkali-rich seems to be at the bottom of a number of misconceptions in Dr. Graton's article. A gas given off by a magma may be acid in reaction and yet be alkali-rich. Fumarolic deposits of volcanic origin have been found by a number of observers (Lacroix at Vesuvius, especially) to contain large amounts of KCl or NaCl or both. In fact, the data seem to indicate that, next to easily volatile substances such as H_2O, HCl, CO_2, H_2S, B_2O_3, these alkalic chlorides are usually the most abundant constituents of volcanic emanations. Dr. Graton has devoted a number of pages of his article to an inquiry as to the source of the alkalic material in the abundant sericite that is commonly present in the wall rock of ore deposits, and to presenting arguments for his belief that it was not leached from wall rock at one place and redeposited at another. The arguments do not appear to me effective in excluding this process as one of the possible sources of alkalic substance, but the likelihood of its derivation direct from the magma should also be kept in view. A magmatic gas that is capable of carrying mineral matter in solution leaves the magma loaded with whatever it has the capacity to dissolve—fully loaded with this material if when it departs it is wholly in equilibrium with the magma. This last condition may not be generally met in full measure.

By such a process of derivation of alkali metals direct from the magma in a vapor state not only may the wall rocks of ore deposits receive additions of alkalic material but in granitization

also this process may be a factor, whatever may be the complete explanation of granitization. In the idea of the transport of alkalic material in acid solutions there is no inconsistency.

Speaking of granitization leads to another point made by Dr. Graton. On p. 215 he states: "pegmatites . . . in any event are now regarded almost universally as representing a *late magmatic* stage." (Italics are Graton's.)

This statement is made as prelude to one on the following page, in which a review of the literature is said to show:

> that in districts where both ores and pegmatites are present, the ores are recorded as younger in so great a preponderance of cases as either to cast doubt on the evidence for the contrary sequence or else to imply that this unusual sequence resulted from special or unusual conditions, even the cutting of ores by pegmatites from a later and independent magma.

This evidence is cited by Graton in opposition to the relations that he supposed must result from the departure of the ores from the magma in a vapor phase, as I had argued. This brings up several matters for comment.

First—do pegmatites represent so generally a late magmatic stage? Granitization is probably accepted by most geologists as a common process. Commonly granitization is accompanied by injection of material, either in lit-par-lit attitude or in transverse veins or dikes, that has all the appearance of common pegmatite. Moreover, several geologists who have made special studies of granitization have concluded that this phenomenon is due to the emplacement of some sort of emanation or derivative of the magma advancing ahead of the main body and later followed by an invasion of the main fluid magma. This implies that emplacement of the pegmatitic bodies occurred at an early stage of magmatic evolution.

Second—probably most geologists would agree that ore deposits are generally derived from large bodies of igneous material, perhaps, in places reaching dimensions of hundreds of cubic miles. At any given time the different parts of such a body, both laterally and vertically, would be in different stages of development. From one part pegmatitic fluids might be given off and from another part ore-bearing fluids. Which cut the other would be largely a matter of chance.

Third—in my original article, in giving reasons for believing that ores are transported in a vapor phase I adduced evidence that seemed to show that in certain instances important metallic deposits had been formed at such an early period in the history of a magmatic body that the emanations coming off from it must have been gaseous. The point that I desired to make was that if in these cases ores came off in the gas phase it was reasonable to suppose that they did the same in other cases where evidence, one way or the other, was lacking. In emphasizing this evidence I may have given the impression that I believed the metallic constituents always departed at an early stage. On the contrary, I should suppose that their evolution should continue as long as emanation of gases is an important factor.

In my presentation, evidence for the theory of gaseous evolution was believed to lie in the often observed clustering of ore veins around plutonic cupolas. The argument was that while the magma in the cupolas was liquid they should serve as collecting "domes" for gases rising through the main body of magma, and thus bring about the observed results, but after crystallization had advanced so far as to solidify the magma in the cupolas and to some depth below there would be no evident reason for ore-bearing fluids of any kind to be directed toward the cupolas. Since the ore fluids were thus early they could not have been liquids residual from advanced crystallization.

Regarding this evidence Graton writes as follows (p. 217):

> The one advantage in Fenner's concept of timing and separation of the ore fluid is that it permits an explanation, otherwise as yet wanting, for the observed tendency of ore deposits to be more numerous in and near "cupolas" and other peripheral parts of intrusive bodies than within their central and deeper portions. But this rather *general* and *vague*[2] phenomenon, explained permissively but not compellingly or exclusively . . . by early gas separation, seems insufficient to offset the more specific difficulties already outlined, such as granitized aureoles[3] and the time-relation of ores to pegmatites.

This is followed by a footnote in which E. S. Moore is quoted as showing that in many examples ore solutions moved up the

[2] Italics mine.

[3] I am not certain that I understand clearly Graton's argument regarding granitized aureoles.

flanks of important synclines, and suggesting "that in these cases, at least, the influence of magmatic cupolas does not seem to govern." This misses the argument. I did not suppose that cupolas are necessary for the formation of ore deposits, but that *where* ore deposits are clustered around cupolas, this indicates emanations in a gaseous condition. Of course, ore solutions, whatever their nature, may move out through any suitable channels.

A little farther on (p. 219) Graton gives at least partial recognition to the force of my argument in this statement:

> With a great volume of still liquid magma (and a possible thin shell already crystallized) Fenner's idea seems to provide a good chance for the rising gas bubbles to segregate upward and to penetrate as a separate and distinct phase into whatever openings exist in the overlying rock container. This, obviously, is a condition that must be met to explain most epigenetic ores. That is to say, there must be abundant selective migrations of the ore-fluid fraction away from the other magmatic material.

On p. 221 Graton follows a similar line of thought and makes an important deduction, with which I heartily agree. It presents clearly conditions that must be met in formulating an acceptable theory of the nature of the ore-forming fluid:

> But it must be recognized, in any event, that the operation of boiling, which interposes a clean-cut interface, whether extensive or very local, between the source-liquid and the evolved gas, is obviously well suited to effect a sharp separation of compositions. And to whatever extent these two phases are segregated into large volumes, mutually exclusive, the mechanism affords a plausible explanation for the observed striking contrast in character between ores on the one hand and the igneous rock or the pegmatite on the other, as well as for the localized position of ores. Despite any other drawbacks, this is obviously a strong tally in favor of the concept of boiling, since . . . no one else has presented with complete clearness an equally simple and effective means of separation and segregation of the special ore fluid as a *liquid*. If the other consequences of separation as gas were equally advantageous and tenable, the controversy as to the nature and state of the ore-bearing fluid would probably long ago have subsided.

This means, in effect, that the ore fluid must separate from the main magmatic liquid either as a gas (as advocated by Bowen and by me) or as a special liquid (as advocated in succeeding pages by Graton). No other possibility seems to be in accord with requirements.

On p. 233 Graton quotes the following paragraph from my article:

> As a plutonic body that is the source of the gases cools in the course of time, the level at which the pneumatolytic condition of the evolved material gives way to the hydrothermal condition descends, until it is finally close to the magmatic source.

Regarding this Graton remarks:

> This idea of descent of the level of condensation, indispensable in Fenner's complete hypothesis, seems, nevertheless, extremely unlikely.

In other places in his article (*e.g.*, on p. 249) Graton declares that if the ore fluid leaves the magma as hot acid gas, most of it is likely to reach the surface as hot acid gas.

I am not able to follow satisfactorily the reasoning by which Graton has arrived at these conclusions. To me it seems almost self-evident that *under usual conditions* neutralization of acidity and condensation of vapor will take place. As others may not accept this view, it may be well to present a fuller picture (simplified and generalized for brevity) of the process as I visualize it.

We shall start with a large plutonic body at the time when it has become emplaced in cold surrounding rock. Gases are evolved from this magma. In general, the quantity of gas in the magma-body may be large or small and the amount of ore-forming constituents may vary similarly, for the formation of ore veins in association with plutons is rather exceptional. Exact figures cannot be given for the volatile content and we can only say that, as magmas go, the one under consideration is supposed to be rather gaseous.[4]

If structures are present in roof and wall rocks which offer such easy escape of gases that any given portion of them is in contact with colder walls for only a short time, the emanations may pass as gases all the way to the surface, as Graton supposes. If, however, even the most favorable channels that are present are much obstructed, as in fracture zones packed with comminuted

[4] To give at least some sort of quantitative picture, I have calculated that a four mile cube of plutonic magma, containing 1 per cent of gases holds seven billion (7×10^9) tons of gas. If the gas content is five per cent, it contains 35 billion (35×10^9) tons.

rock débris for thousands of feet, the gases will only slowly struggle upward.

After emplacement heat is conveyed outward both by bodily movement of gases and by conduction from the magma and from the gas channels through roof and wall rocks. A wave of increasing temperature of enclosing rock characterizes the preliminary stage. However, heat conduction through rock is a very slow process, and the mass of the roof rock is many times greater than that of the ore fluid. Under the conditions conceived a temperature gradient would be established such that at the surface the temperature would be much below that at the source. Along channels through which emanations were passing, temperatures would be higher than in the walls, but if the passage of emanations were slow, their temperature would be only slightly higher, as they would constantly give up heat to the walls, and before the surface was reached condensation would occur.

However, one must take account of the complex make-up of the gases as they leave the magma. Water vapor, which is presumably the chief constituent, would be one of the latest condensed. Halide compounds of the alkali metals, of the heavy metals, and of silicon, together with phosphorus, boron, and others in possibly unknown combinations, and accompanied by anything present that is non-volatile itself but which is soluble in the other vapors at the extreme temperatures and pressures prevailing at the source, all these are likely to drop out in large measure before there is much condensation of water vapor. Carbon dioxide and H_2S, on the contrary, may continue as gas to the end, unless they combine with bases in the walls. A further complication is introduced by the fact that volatility of compounds of the heavy metals in a vapor in which H_2S is a constituent is rendered possible (or, at least, greatly increased) by the presence of free halide acid. As the concentration of free acid is gradually reduced by reaction with wall rocks in the lower part of channelways metallic sulphides are precipitated. This neutralization of acid may be effected by its combining not only with alkalic oxides but also with Al_2O_3, Fe_2O_3, FeO, CaO, MgO, etc. present in rock minerals.

The whole process of evolution of gases from the magma, their movement through channels in the walls, the chemical reactions they undergo, and their final condensation, one after another, is necessarily complex, but though details are complex and can only be expressed in a general manner, underlying principles are simple and are based in their main features on direct observations, involving a minimum of assumptions. The first observational matter is the prodigious gas pressure that is demonstrated in many volcanic eruptions. It seems capable of forcing gases out from a plutonic mass against very great frictional resistance encountered in the pores of wall rocks. Apparently very high gas pressures are present in some magmas, while they are almost wholly liquid. These pressures do not have to wait for development until crystallization has concentrated the gases in a small amount of residual liquid, although the pressure may increase as crystallization proceeds.

The second observational matter concerns the ability of the magmatic gases to carry mineral matter. Metallic ores and other mineral compounds have been found in volcanic regions under conditions that show that they were brought to the surface in a vapor phase. These minerals have been discovered in places in rather large quantities, though often under circumstances that indicate they could hardly have been more than an infinitesimal fraction of the total content carried by the evolved gases.

Having these observational data at hand we have made use of what chemical and physical principles seem applicable to explain them.

Thus far the discussion of these matters has been concerned with the first stage following the emplacement of the pluton—the stage in which a wave of rising temperature advances into roof and wall rock. During this stage a vapor phase may or may not extend all the way to the surface, but even when it does an important part of the load of the gases is likely to be dropped along the way unless the gases have an almost unobstructed passage. This dropping of load is ascribed to cooling of the gases as they move outward, to reactions with walls and obstructing matter

along the way, and to internal reactions among the constituents of the gases.

Under the conditions conceived, the temperature at the source is a maximum immediately after the emplacement of the pluton, but the crest of temperature, as it moves out into overlying rocks, is likely to lag considerably behind, and at any point in upper regions the maximum will be reached later. This is analogous to the penetration of summer heat into the surface soil of a region.

Consequent upon the loss of heat from the magmatic mass the temperature at the source necessarily begins to drop, though possibly many years may supervene before the magma becomes so nearly dead that no effective quantity of gas is evolved.

Although the crest of temperature at any level in the overlying rocks may be reached somewhat after the emplacement of the pluton, there will always be a gradient of decreasing temperature from the source outward (otherwise the pluton would not cool).

Conditions in the long period following the first wave of rising temperature may be looked upon as representing a second stage, though obviously there is no break. Disregarding what may be regarded as an unusual condition, namely, almost unobstructed passage of gases outward, they can be considered as moving slowly along certain channels, and the whole system, pluton and emanations, cooling off. The region of lowest temperature is at the surface, for it is from the surface that all heat finally escapes. Ultimately the plutonic source becomes cold and dead, but before this state is attained there must be of necessity, so far as I can conceive, an intermediate range of conditions during which the water vapor becomes condensed to liquid in the upper part of the channels while it is still in the vapor state below, and as the system cools the interface where condensation of water occurs moves downward.

Dr. Graton argues that even if some water in the emanations is condensed to a liquid in the upper regions, gas is able to bubble through it and has little or no power to expel liquid. On this matter Ingerson and Morey in their discussion, have taken essentially the view of obstructed passages offered here. There seems

to be, however, a question of fact involved as to the porosity or tightness of the ore channels, and it would be interesting to have the opinions of other geologists and mining engineers on this matter. As a result of my own experience during several years practice as a mining engineer and through observation of underground conditions in many mining regions, I became firmly impressed with the view that, except near the surface, no structure is commonly found, either porous layer, plane of faulting, or zone of crushing, that would afford such free passage of gases as Dr. Graton's view seems to require.

Advocates of the theory of "ore magmas" have pointed to breccias and horses of country rock entirely surrounded by ore and gangue as evidence of the injection of ore magmas into cavities, but probably most geologists would look upon such fragments as having been originally supported by finer débris, now replaced by vein material, and would not accept these occurrences as evidences of open chambers. Possibly some vugs or pockets lined with crystallized minerals represent original cavities, but that need not imply an open fracture of more than small extent; and there is much question whether these vugs may not often be a partial filling of solution cavities. In the especially porous rocks that form reservoirs of petroleum, artificially applied gas pressure is able to drive petroleum out of the pores of the rock ahead of the gas.

Some may raise an objection (which Graton does not offer) that even if an interface were formed between condensed liquid above and gas below, this would be a static condition and the gas would not continue to force liquid upward. To this the obvious reply is that although the position of the interface is stationary there is no implication here that material does not move across it, condensing from gas below to liquid above. The load on the gas would not be increased, for the addition of condensed material at the interface would be compensated by overflow at the surface.

On a previous page of this discussion the statement was made that gases escaping from a magma will (if in perfect chemical equilibrium with the magma) carry the full load of magmatic

mineral matter of which they are capable. It may occur to some to ask why, in that case, their supposed acidity should not have been completely neutralized before leaving the magma, or if they have not become neutral, how they can attack wall rock later, since they have taken up all the basic matter that they can hold. In not supplying an answer to these questions in my previous article I left open an opportunity for attack. Dr. Graton seems to have missed this, but it is likely to occur to him later unless the ground is covered. The explanation lies in an amplification of certain statements made in my previous paper (p. 79).

Reference was made there to the rather famous experiments of Gay-Lussac and Thénard in 1809, more recently reinvestigated quantitatively by Clews and Thompson. When a mixture of NaCl and SiO_2 was heated in a current of water vapor at various temperatures up to 1045° C., variable amounts of HCl were given off according to the equation:

$$2x\ NaCl + y\ SiO_2 + x\ H_2O \rightleftarrows x\ Na_2O,\ y\ SiO_2 + 2x\ HCl$$

A small quantity of Cl also was produced. The evolution of HCl is just discernible at about 600° C. Rise of temperature and increase of the supply of moisture augment the quantity of HCl evolved.

Two points are to be noted. In a two-phase system of this kind equilibrium does not require all the acid in the gas phase and all the alkali in the solid (or liquid) phase to be neutralized, but permits them to be separated; and the dissociation becomes greater (as shown by increased concentration of HCl) with increased temperature. The latter effect is in accordance with the Le Chatelier theorem that, with rising temperature, reversible reactions tend to proceed in the direction that absorbs heat.

It is believed that this experiment, though simple, is sufficiently analogous to magmatic conditions to explain the observed fact that emanations from magmas, although loaded with mineral matter, may still contain free acid, and to show that as these acid emanations move out from the magma into colder rock they tend to react with the rock and extract bases.

On p. 279 Graton quotes the following paragraph from my article:

> When a bubble consisting chiefly of such gases as those mentioned (H_2O, HCl, CO_2, H_2S, etc.) rises through a magma, it serves as a collection chamber for other gases of very small vapor pressure. The latter are distilled into the bubble essentially as if it were a vacuum, no matter what pressure it may actually be under. This dynamic action . . . should be very effective in collecting and sweeping out from the magma substances of small to moderate vapor pressure.

To this Graton urges the objection:

> It is . . . to be remembered that this dynamic method of promoting abstraction of low volatile components is effective in proportion not to the mass but to the *volume* of the gas bubble acting as collector. Therefore, all other conditions being equal, the method is far more efficient under a pressure of one atmosphere than under thousands of atmospheres in a magma chamber. The volume of the gas under these latter conditions is relatively insignificant, . . . and the efficiency of the process in its geological applications must be correspondingly slight.

This objection of Graton's appears, at first sight, to be valid and to be destructive to the idea. Probably the same objection to the transfer not only of ore substances but of mineral matter of any kind by gas bubbles rising through a liquid magma has occurred to others. It is desirable, therefore, to expand the idea at greater length than I have previously done, and to apply an important principle that I failed to cite before. This is the principle of differential stress.

This principle states that when pressure or other stress is applied to one of two phases in mutual contact and not to the other, the tendency of material to escape from the stressed phase into the unstressed phase is correspondingly increased.[5] This carries the very important implication that, if there are no modifying influences, both the absolute and the relative quantities of the constituents of the gas bubble are essentially the same whether its total volume be great at one atmosphere or small at 1,000 atmospheres.

To inquire what modifications are necessary, further analysis may be made. My understanding is as follows:

[5] An analogous phenomenon, explained by the same thermodynamic laws, and more generally known, is the melting of ice under pressure. The water that escapes to an unstressed position immediately recongeals.

When a liquid is subjected to hydrostatic pressure the resistance of any portion to the surrounding pressure is due chiefly to resistance of its molecules to being brought closer together. Whether the liquid be homogeneous or heterogeneous, each molecule bears the same stress. The situation is one of static resistance. With gases the situation is very different. In these the resistance is dyamic—outside pressure is supported by the violent battering of thermally agitated molecules against the walls. Each molecule acts independently of others and each kind of molecule contributes pressure in proportion to the quantity present. From this, the well-known principle follows that each gas in a mixture adds its own pressure as if other gases were not present.

It seems evident from the preceding that all the molecules of potentially volatile substances, while dissolved in a stressed liquid, bear the same stress as the surrounding molecules, but if the quantity of some of these is small, then by escaping into a gas bubble in which other volatile substances are preponderant they bear only a small fraction of the pressure, the greater part being borne by the preponderant gases. It is as if they were squeezed from a position of great stress in the liquid to one of very little stress in the gas.

In the passage quoted Graton speaks of the "relatively insignificant" volume of bubbles at a pressure of thousands of atmospheres in a magma, and others have written as if they supposed a large bubble at the surface would be a mere pin-head at such depths. Let us consider a spherical bubble having a diameter of 1,000 inches under one atmosphere pressure. At a depth of three miles in a magma, where the pressure would be, roughly, 1,000 atmospheres, its spherical volume would be reduced to 1/1000 of the above, but its diameter would still be 100 inches. For bubbles of such large size as those seen in photographs of the lava pit at Kilauea a reduction to 1/10 of the diameter would leave a sizable bubble. Doubtless reduction of volume to 1/1000 would modify internal conditions considerably, so that the idea of its representing a vacuum for the lesser gases would no longer strictly hold, but the volume is yet far from having reached the

small volume of a liquid. A calculation on the assumption that gas laws hold under these extreme conditions shows that water gas at a temperature of 1,000° C. and at the pressure of 1,000 atmospheres would have, roughly, 5.8 times the volume of ordinary liquid water. Of course, gas laws do not hold strictly. The compressibility of the gas would have become less, which would leave the bubble larger than calculated, but the idea of a vacuum in respect to the minor gases would have to be modified, as the resistance to outside pressure would no longer be due wholly to the dynamic battering of agitated molecules, but partly to their opposition to being brought more closely into mutual contact.

Another modifying influence that must be recognized is the increased solubility of gases in surrounding magma as pressure increases. At one time it was assumed that even at very high pressure this increase obeys Henry's Law, that solubility is directly proportional to pressure, but Goranson's experiments have pretty well disposed of that. He has shown that in the systems he investigated the curve of solubility at high pressure takes a direction almost at right angles to the coordinate of pressure. Increased pressure increased solubility very little.

However, the effect of pressure on solubility may not be as important as it might seem, under the conditions we are considering. If, after emplacement, the magma body reaches a somewhat static condition (that is, one not greatly disturbed by convection currents) its upper levels will arrive at a state approaching equilibrium of solubility with respect to gases passing through it. There will also be a tendency to bring about equilibrium of chemical composition between magma and streaming gases, that will result in differences of composition between bottom and top of the plutonic mass.

To summarize—The principle of differential stress seems to remove in large measure the objection that Graton raised in respect to the small volume of gas bubbles at depth in a magma. Doubtless at depths of many miles gas laws are so greatly modified that his objection would hold. Possibly at even those extreme depths gases may be set free if the body of magma has

recently risen from still greater depths, and thus the load on it has been reduced, but there is little likelihood that they can serve effectively as vacuum chambers for minor gases. As a bubble rises, however, its volume increases and the vacuum chamber effect also increases. It seems likely to be important at depths of a few or several thousand feet. Moreover, change of pressure and temperature affects the equilibrium of the mixture of gases within the bubble and likewise their equilibrium with the surrounding magma, and there is interchange of material between the two phases as the bubble rises, all of which tends to bring about differences of chemical composition between the lower and upper parts of the pluton and to carry mineral matter from the upper parts out into the roof. With the advance of solidification of the magma, more and more gas is forced out of the residual liquid and brings about metamorphic effects.

Analysis of the objections brought to the fore in Graton's argument does not seem to necessitate any important departure from views previously expressed, that gas bubbles rising through magma chambers are effective agents in transferring mineral matter from lower to higher levels and out into surrounding rocks.

Graton objects to the importance that I ascribed to the halide elements as ore carriers because of the small quantity of Cl and F commonly present in rocks adjacent to ore bodies. He cites (p. 269) as an example the occurrence, in the Cerro de Pasco district, of a single body of sulphide, chiefly pyrite, containing 500,000,000 tons between the present surface and the bottom level at 2,100 feet:

> there is nowhere in the district known chlorine or fluorine to serve as remaining clue, however slight, of hundreds of millions of tons that would have been required to pass through a single channelway in order to form this one mineral body.

A similar objection has been expressed by other writers, not only in respect to transport of ore minerals but also to transfer of mineral matter in general in a vapor phase. Sometimes this objection is phrased with an air of finality that indicates the belief that it is a crushing blow to the theory. Nowhere have I seen mentioned what seems an obvious answer.

Instead of gases Graton favors a dilute alkaline liquid (p. 337), containing, say, 90–95 per cent water (p. 329, footnote), this liquid having been derived directly from the main body of magma. A similar alkaline liquid as an ore carrier is a common conception, and I have expressed the belief that such a liquid, similar in properties to the one advocated by Graton but formed in a very different manner, is, of necessity, eventually produced from the acid gases by condensation and by reaction with wall rocks, and is important in the late phases of ore deposition. In regard to Graton's objection to halides in the early stages a crucial question may be put: What keeps the sulphide ores in solution in his dilute alkaline liquid and enables them to be transported? The usual answer is that their solution is rendered possible by an excess of alkaline sulphides. This seems a reasonable explanation, and I have endeavored to show in my original article how such a liquid is likely to be formed. But this leaves us in the same quandary (if it is a quandary) as is that caused by the disappearance of the halides. The question now is, what becomes of the vast amount of excess sulphur of the alkaline sulphide? A small portion is sometimes locked up by the transformation of original iron minerals into pyrite, but that is far from a satisfactory and complete answer for such an occurrence as the Cerro de Pasco body. Graton's figures show that it is nearly pure pyrite. It must have been transported to its present position in some solution in which it was soluble, and the excess sulphur of the alkaline sulphides has vanished as completely as the halides to which Graton objects. The answer to this problem and to several similar ones probably lies in the fact that magmatic "mineralizers" in general (French "minéralisateurs") do not generally form stable petrogenic minerals. They are brought to the surface and washed away.

An illuminating example of this action is supplied by borate minerals. Deposits are found in many volcanic regions, and there is general acceptance of the view that their boric acid has come from magmatic emanations. In southern California are found beds, deposited in recent or older playa lakes, which contain

enormous quantities of borates. Presumably boric acid has in many places traveled up through the rocky crust, yet boron compounds are of sparse occurrence as rock-forming minerals.

Graton (p. 304) quotes with approval a statement made by Schaller:

> Pneumatolytic processes—that is, gas-phase conditions—might well have enough energy to bring in considerable material, but after reaction, it hardly seems likely that enough energy will remain to remove all of the replaced material in a gas phase. Such a condition alone would seem to favor a hydrothermal process as the more likely one to effect at least the removal of the material replaced.

I have not been able to understand the basis of Schaller's statement. If a set of reactions occurs by which a gas forms certain new minerals and removes, in part or as a whole, certain old ones, each reaction is accompanied by an energy change, which may be negative or positive.[5] I do not know of any principle by which one can determine in advance what the total net energy change for the set of reactions will be, or whether it will be positive or negative. Even a negative change need not inhibit the reactions; they simply acquire energy from their surroundings. In any event, there is as much or as little justification for raising the same objection to the reactions of a liquid solution.

In several places Graton has similarly brought forward difficulties in explaining certain phenomena by pneumatolytic processes without recognizing that like difficulties arise if a liquid solution is favored. As a case in point reference may be made to his citation (p. 309) of occurrences at Cobalt, Ontario, where

> . . . numerous strong but lean quartz veins with base-metal sulphides in the Keewatin lavas undergo almost instantaneous revolutionary change to calcite gangue with abundant cobalt-nickel arsenides and fabulous silver values where they pass upward into the Cobalt conglomerate.

I have no doubt that these ores were deposited, at their present locus of occurrence, from alkaline liquids. The nature of their gangue shows this, and, according to the theory I have proposed, acid pneumatolytic processes of an early stage lead to alkaline

[5] For example, when HF reacts with solid SiO_2 and carries off gaseous SiF_4, much heat is evolved. It should also be noted that "increase of free energy" in the physico-chemical sense does not necessarily mean evolution of heat.

liquids at a later stage. The chief point that I would make here, however, is that I doubt if Graton or any other geologist can give a reasonable explanation of such an occurrence as that at Cobalt without bringing in a great deal of speculation. The remarkable features present a problem under any theory of the nature of the ore-forming fluid.

In my article I had deduced that

> . . . material that has been deposited originally from vapors will ultimately be exposed to a hydrothermal environment which will transport and modify it in a manner comparable to what occurs in secondary enrichment when supergene processes are imposed on "hypogene."

In regard to this Graton argues (p. 241):

> Now an outstanding fact about ores affected by supergene enrichment is our ability to see the products of *both* processes, the one superimposed on the other, to note the distinctive differences between them, and to trace in countless examples nearly or quite complete enrichment gradationally into its unaltered hypogene progenitor. . . . Is it not, therefore, entirely appropriate to inquire whether the same kind of geological evidence which makes secondary enrichment so undeniable has been found for the "comparable" conversion of an early deposit by acid gas into the later ores as we see them?

One may remark that, in comparison with the long period that ore deposits have been studied, it is hardly later than yesterday that the importance of secondary enrichment in the formation of sulphide and similar ores was recognized and that geologists were able to distinguish clearly "the products of both processes." Even after the announcement of the main idea had shown the way, years of discussion ensued as to what were reliable criteria for distinguishing "primary" and "secondary" minerals, whether certain minerals might be, in one case, primary, and, in another case, secondary, and as to a number of minor matters. Probably even now not all of those questions have been settled to everyone's satisfaction. Still, Graton's argument has considerable force. I will attempt to meet it by suggesting two considerations.

First, the zone of secondary enrichment is limited downward by the depth to which vadose waters have been able to penetrate. Valuable information is obtained by studying the nature and

mutual relations of the ore minerals above and below this limit. In the process that I have suggested there is nothing quite similar in that respect. The channels in which ores have been precipitated in early stages are, at later stages, traversed throughout their length by solutions that are of different chemical character but which are still hot and vigorously reactive and in which the ores are again soluble. The tendency is to redissolve the first deposited ores and carry them upward and redeposit them, and this movement is only limited in time and in upward progress by the cooling of the system to such a degree that the chemical activity of these solutions vanishes. The effect is to remove the ores from the situations in which they were first deposited by gases and carry them to higher levels.

It seems to be the belief among ore geologists that the impoverishment of veins with depth commonly occurs long before the magmatic source is reached. The process outlined above is likely to bring about such a result. Even where ores continue downward into the upper part of the parent pluton, yet solutions from greater depths have acted upon them. Veins are followed in mining only so far as there is hope of finding payable ore. What has happened along the channelways between the point where mining has been discontinued and the source is practically unknown from any direct observation. In many places the present level of erosion must have revealed examples of these lower, barren portions of channelways whose upper portions carried rich ores, but they have seldom been identified. Difficulty arises from the fact that there is a considerable variety of transgressive bodies of rock, of metamorphosed or replaced or infilled character, among which to choose as representing the lower parts of ore veins.

Second, in partial agreement with Graton's idea it may be said that in the great variety of natural conditions under which deposition by gases would be followed by attack and redeposition by liquids, there is a probability that ores deposited by the two processes at their respective stages would sometimes occur in contact, and it might be supposed that clear evidence of the two would then

be found. Now, in secondary enrichment many of the ore minerals are of different composition from those of primary deposition. How far would geologists be able to get in this matter if all the minerals were the same? That seems to be about the situation in respect to gas-deposited and liquid-deposited ores. In secondary enrichment the fact that one mineral cuts another is a helpful criterion, but many examples are known in which movement and cracking of vein material have occurred during primary deposition, sometimes repeatedly, and transgressive veinlets have thus been formed in which one primary mineral cuts another. This phenomenon, by itself, is not reliable. Among minerals collected in fumaroles in the Valley of 10,000 Smokes, magnetite, pyrite, galena, sphalerite, and covellite were prominent. The same minerals are commonly ascribed to deposition by hot liquid solutions of alkaline sulphides. Similar gas-deposited minerals to those mentioned have been commonly reported in other localities. In fact, I do not know of any metallic ores that are known to have been deposited by gases that might not be deposited by alkaline liquids also. This increases greatly the difficulty of distinguishing between the two groups.

These two considerations seem to go far toward explaining why evidences of the different processes are not obtainable so readily as in secondary enrichment.

On p. 281 is a statement by Graton as follows:

> it is evident that no more of those latter elements (ore metals) can be so transported in the gaseous phase than can combine with the *scanty* Cl and F present in the magma. (Italics mine.)

This is followed by a calculation, made by H. C. Anderson under the supervision of Prof. G. B. Kistiakowsky, on the allocation or partition of Cl and F among the elements in a typical granitic magma, and a calculation of the resulting partial vapor pressures. Graton attributes great importance to the results obtained, and concludes:

> . . . it is immediately evident from these figures that, aside from water and a very subordinate proportion of free halogen acids, sodium and potassium are the only mineral-forming elements that can be transferred away from the magma in quantities of the slightest significance.

In making these calculations certain simplifying assumptions

were necessarily introduced regarding entropy change, heat of reaction, heat of solution, and non-participation of certain volatiles. Apparently this simplification required that no account should be taken of the important changes of energy caused by the complex set of reactions that occur when the potentially volatile constituents, upon relief of pressure, are set free from the combinations in which they existed in the magma and re-group themselves into the actually volatile compounds that escape, while at the same time the magmatic elements left behind likewise re-group themselves. I have the greatest doubt if in such a complex substance as a plutonic magma there is yet sufficient knowledge to give validity to quantitative figures of this kind. The calculations made in my article on the application of the law of mass action, were, by comparison, of great simplicity. No attempt was made there to arrive at comparable quantitative figures, but the purpose was to show how certain fundamental laws would operate. In any event, the calculations cited by Graton, if they prove anything, prove too much. In the Valley of 10,000 Smokes the quantities of metallic minerals deposited by gases were decidedly not insignificant. The magma body under the Valley was probably small, as energy declined rapidly in a few years. In other regions, as around certain volcanoes, fumarolic minerals in probably greater quantities have been found, but the size of the magma body from which they emanated is not known.

In the foregoing pages I have attempted to give an answer to some of the more important objections brought forward by Graton in regard to my conception of the nature of the ore-forming fluid. It is a subject in which there are so many unknowns that one cannot hope to present a picture that is free from difficulties and that will not have to be modified later. Graton has done a great service in making a clear-cut distinction between two fundamentally different ideas as to the nature of the fluid when it leaves the magma. Others should follow this up by contributing observational or theoretical evidence favoring one or the other process.

C. N. FENNER.

CLIFTON, NEW JERSEY,
July 15, 1940.

THE GEOCHEMISTRY OF QUICKSILVER MINERALIZATION.

Sir: Messrs. Fahey, Fleischer, and Ross are to be congratulated on their prompt discussion of the recent paper on "The Geochemistry of Quicksilver Mineralization."[1] Unfortunately, however, their communication contains a number of direct mis-interpretations of statements presented in the paper under discussion.

On page 470 of their discussion, Fahey, Fleischer, and Ross state:

> Dreyer on pages 151–55 contends that replacement was a major factor in the formation of many quicksilver deposits in contrast to Becker's concept that essentially all cinnabar has been deposited in open space. . . . As thus viewed, the arguments put forth by Dreyer are not so much opposed as they might appear at first glance to the essential concept that in most kinds of quicksilver lodes ore of commercial value is localized only where abundant open spaces were available at the time that the cinnabar crystallized.

Far from contending that replacement was a major factor in the formation of many quicksilver deposits, the writer has clearly stated the following (p. 154):

> There can be no doubt that, in the first instance, quicksilver mineralizing solutions have gained access into the country rock through intergranular openings and fractures. The occurrence of cinnabar in such openings and fractures commonly accounts for by far the greater percentage of cinnabar in the ordinary quicksilver ore. However, whenever the concentration of cinnabar in any small area becomes so great that the available openings are filled, the cinnabar bearing solutions are quite capable of replacing components of the wall rock and such replacement is by no means an uncommon feature of quicksilver ores.

The remainder of the discussion (pp. 152–54) is simply an exposition (supported by empirical petrographic data and photomicrographs) of the not-too-startling fact that, in general, some replacement has also accompanied the major process of open space filling during quicksilver mineralization. The writer has noted the fact (pp. 152–3, Figs. 5 and 6) that ore occurring in sandstone in the Oceanic, New Idria, and Sulphur Bank mines shows, in individual specimens, all gradations from cinnabar occurring as

[1] Dreyer, R. M., The geochemistry of quicksilver mineralization: ECON. GEOL., 35: 17–48, 140–57, 1940.

simple open-space fillings to massive cinnabar which has completely replaced the adjacent country rock. The paper likewise presents (pp. 153–4, Fig. 7) a demonstration of the fact that many of the cinnabar veinlets filling fractures are not sharp walled in detail, but rather are quite ragged. There is, therefore, no doubt that some replacement has accompanied the major process of open-space filling.

Fahey, Fleischer, and Ross criticize the writer for his suggestion that replacement may not be molecular in character as postulated by Becker in 1888. In support of this criticism, they cite a statement by Lindgren.[2] Lindgren's statement is as follows: "The word metasomatism . . . is now applied to the practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly differing chemical composition may grow in the body of an old mineral or mineral aggregate." There is no portion of this statement that can be taken to contradict the concept that replacement is effected by the solution and consequent deposition of a large number of molecules rather than by a simple molecular interchange. This concept of molecule for molecule replacement advocated by Fahey, Fleischer, and Ross (p. 470) is, however, specifically refuted by a recent statement by W. H. Emmons[3] reading as follows: "The absence of microscopically visible spaces in many altered rocks has led to the statement, frequently made, that the new substance has replaced the old 'molecule by molecule.' This expression has not been in much favor in recent years because the theory encounters chemical difficulties. There is room, even in a sub-microscopic space, for myriads of molecules, involving various reactions."

On p. 469, Fahey, Fleischer, and Ross state: "The intimate mixture of pyrite and marcasite with cinnabar and metacinnabar in the ore of the Mount Diablo mine, Cal. . . . lends little support to Dreyer's conclusions as to the mode of origin of the different forms of mercuric sulphide." The writer made no statement whatsoever to the effect that the interesting mineral as-

[2] Lindgren, Waldemar, Mineral Deposits, 4th ed., p. 91, 1933.

[3] Emmons, W. H., Principles of Economic Geology, 2nd ed., p. 159, 1940.

semblage at Mount Diablo lends support to any theory relating to the genesis of the mercuric sulphides. The discussion of the type of iron disulphide associated with quicksilver deposits (pp. 148–51) does, however, present good evidence in support of a variation in the chemical character of the mineralizing solutions during the period of mineralization.

Objection is made to the writer's assertion that there exists a close genetic relationship between silica and cinnabar in many quicksilver deposits. This close relationship was noted not only in a Nevada "opalite" deposit (as intimated by Fahey, Fleischer, and Ross—p. 469), but also in several California quicksilver ores occurring in silicified serpentine (*cf.* pp. 145–6). Nowhere is it stated either that all quicksilver deposits have undergone silicification or that silica is always closely genetically related to cinnabar. The evidence presented (pp. 140–46) is simply petrographic data derived from the study of a large number of thin and polished sections made from a wide variety of quicksilver ores. Such petrographic evidence strongly indicates that at the Goldbanks, Nevada, deposit as well as at several of the California deposits in silicified serpentine there is a very close genetic relationship between cinnabar and silica.

Fahey, Fleischer, and Ross state (pp. 468–9): "Dreyer's reasons for dismissing reductions by organic compounds as a cause for the occurrence of native mercury are not convincing. Coal and charcoal which are the only organic substances considered by Dreyer are much weaker reducing agents than many of the bituminous substances found associated with cinnabar." The following statement was made in my paper (p. 38): "It is probably true that organic compounds can be found which will reduce the mercuric sulphide to native mercury." The writer then simply presented evidence that, if such compounds exist, they are compounds other than those existing in coal. Moreover, native mercury occurs at a number of places where hydrocarbons are notably absent. The writer has cited (p. 39) the occurrence of relatively large amounts of native mercury in unaltered basalt at Sulphur Bank at places in which hydrocarbons are not present. Moreover,

Fraser [4] has noted the occurrence of relatively large amounts of native mercury associated with certain epithermal gold-silver ores. Hydrocarbons are not present in these ores.

On p. 468, Fahey, Fleischer, and Ross discuss the fact that mercuric sulphide can be precipitated by dilution and gradual neutralization in an alkaline solution. This gives corroboration to an experiment described by the writer on pp. 37–8 by means of which the same conclusion was reached. The point which the writer was making and which Fahey, Fleischer, and Ross appear to have overlooked is that the mercuric sulphide thus precipitated is the black mercuric sulphide (which is rare or absent in many quicksilver deposits) and that it would then be necessary to find some probable method by means of which the metacinnabar could invert to the far more common cinnabar.

The greater portion of the remainder of the discussion is concerned with a consideration of monotropism in relation to metacinnabar inversion. Fahey, Fleischer, and Ross state (p. 466): "He seems not to have realized the meaning of their proof that metacinnabar is a monotropic form of mercury sulphide. The fact that metacinnabar is a monotropic form means simply that it is metastable with respect to cinnabar under all conditions. . . . It must be borne in mind that laboratory experiments performed in the limited time that marks the duration of all human endeavor only point the way to an understanding of processes that continue throughout geologic time." Far from not realizing the implications of monotropism, the writer has gone to considerable length (p. 36) to cite reasons for believing that most cinnabar deposits have been formed primarily as cinnabar and that the cinnabar has not resulted from the later inversion of metacinnabar at low temperatures over a long period of geologic time. The reasons cited for this belief are (1) the fact that metacinnabar is notably absent in many deposits whereas, if cinnabar has formed commonly by the inversion of metacinnabar, it would be expected that at least small quantities of residual metacinnabar would be found in many

[4] Fraser, H. J., Genetic correlation of cinnabar and some gold-silver deposits (abstract): Econ. Geol., 34: p. 468, 1939.

deposits; *i.e.*, that in many cases the inversion might not be expected to have gone to completion and (2) that the metacinnabar content of a deposit should be inversely related to the age of deposition if the cinnabar has formed from the inversion of metacinnabar. That some of the most recent deposits contain no metacinnabar is regarded by the writer as evidence (not proof) that the primary precipitate was cinnabar (not metacinnabar). For the reasons stated above, it is believed that, in most cases, the primary mercuric sulphide precipitate was cinnabar and that the presence of cinnabar as the predominant mercuric sulphide in most quicksilver deposits has not, therefore, resulted from any slow inversion of metacinnabar over geologic time. The temperatures of mineralization to which Fahey, Fleischer, and Ross voice objection are admittedly only those temperatures above which cinnabar forms the greater part of the primary precipitate under the given conditions of acidity or alkalinity. Since it is believed that in most cases cinnabar was the primary precipitate, it is likewise believed that the temperatures cited approach those at which cinnabar must have been deposited naturally. Accordingly, before it is possible to accept the concept that most quicksilver deposits may have resulted from the dilution, neutralization or acidification of hypogene solutions, definite proof must be presented that most cinnabar deposits have formed by a slow inversion of metacinnabar over a long period of geologic time.

ROBERT M. DREYER.

UNIVERSITY OF KANSAS,
June 6, 1940.

REVIEWS*

Organic Reagents Used in Quantitative Inorganic Analysis. By W. PRODINGER. Translated by S. Holmes. Pages 203. Elsevier Publishing Company, Inc., New York, 1940. Nordemann Publishing Company, Inc., Distributors. Price, $5.00.

For the first time chemists interested in analytical work have offered to them in this little book an account of the increasing use of organic reagents in the accurate and rapid determination of metallic elements in mineral mixtures and alloys. A "general part" of 30 pages deals with the reagents employed in the described analyses and a "special part" with the methods employed in separating the various common and rare metals from one another, and in determining the amounts of those present in association with others from which they are separated with difficulty by the usual methods of analyses. Gravimetric, volumetric and in some instances micrometric processes are discussed in considerable detail, and statements are made as to their delicacy and the exactness of the resulting determinations.

The book should be of considerable help to those who have to work with minute quantities of metallic elements in mixtures.

W. S. BAYLEY.

Geology for the Layman. By A. MACLEAN. Pp. 168; Figs. 33. Northern Miner Press, Toronto, 1940. Price, $2.00.

This little flexible pocket book originated from a group of lectures by the author prepared at the request of a group of business and professional men who were interested in mining affairs but who lacked familiarity with geological and mining terms and usages. It deals with Materials of the Earth's crust, Igneous rocks, Weathering and erosion, Folding and faulting, Intrusions, Metamorphism, Ore Deposits and Historical Geology. It is a handy, readable, little book that should serve well the purpose for which it was written.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Mines Register, Vol. 20, 1940. Pp. 942. Atlas Publishing Co., New York, 1940. Price, $25.00.

This comprehensive successor to the Mines Handbook and Copper Handbook follows the 19th volume after an interval of three years. The many changes in the mining industry in North America, particularly those resulting from the war, such as new mining companies, changes in costs, production, etc. have been checked and are now included. The 1940 edition contains descriptions of more than 7000 active mining companies and lists 24,000 inactive mines, an increase of 30 per cent over Volume 19. Section 1 contains descriptions of the active mines of the Western Hemisphere; Section 2, of larger mining companies in other parts of the world; Section 3 is addenda to Section 1 and Section 4 lists the inactive mines. There is also included, as before, statistics on metal production, consumption, imports, exports and price trends; lists of mining engineers and executives, securities with high and low prices and a buyer's guide.

This volume is one that should be available to all interested in mining.

Weather Analysis and Forecasting. By SVERRE PETTERSSEN. Pp. 505; Figs. 249. McGraw-Hill, New York, 1940. Price, $5.00.

This comprehensive and authoritative volume, by an outstanding author, deals with principles and theories underlying modern methods of weather analysis and their application to actual forecasting. It is meant for teaching purposes and professional forecasters.

The chapter headings indicate its contents: Air Mass Characteristics, Stability and Instability in Relation to Weather, Production and Transformation of Air Masses, Kinematic Analysis: Wind and Pressure, Frontogenesis, Frontal Characteristics, Waves and Cyclones, Isentropic Analysis, Forecasting of Displacement of Pressure Systems, Fronts and Air Masses, Deepening and Filling, Technique of Analysis and Forecasting.

It is well written, well illustrated with clear diagrams and should prove to be the outstanding reference on this subject.

BOOKS RECEIVED.

WILLIAM E. BENSON.

NORTHERN AUSTRALIA.

Report of the Committee Appointed to Direct and Control the Aerial, Geological, and Geophysical Survey of Northern Australia, for the Period Ended 31st December, 1938. Pp. 93; geol. map in color of the Herberton Dist., 27" × 38", scale 1:63,360; and 5 large, colored plans of various geophysical investigations. Gov't Printer, Canberra, 1939.

Price, 4s. 9d. *Administrative data and a resumé of the work accomplished, with a summary of the geology and mineral deposits studied.*

—— **the Period Ended 30th June 1939.** Pp. 20; pls. 3. Price 1s. *Contains two very illuminating diagrams; one a map 24" × 28" of Australia showing the areas so far covered by this survey; the other a map 26" × 12" with a red overprint showing the parts of northern Australia that appear to show promise of mineral wealth.*

In the January issue of this Journal a number of these interesting short papers were first listed, and it was indicated that many more were forthcoming. The following have been received:

NORTHERN TERRITORY REPORTS.

Nos. 7 and 8. **The Fountain Head Area, Pine Creek Dist.** J. M. RAYNER, P. B. NYE, AND V. M. COTTLE. Pp. 21; 4 maps.

Nos. 9 and 10. **The Yam Creek Area, Pine Creek Dist.** Same authors. Pp. 10; 2 maps.

Nos. 11 and 12. **The Woolwonga Area, Pine Creek Dist.** J. M. RAYNER, P. B. NYE, AND A. H. VOISEY. Pp. 15; 3 maps.

Nos. 13 and 14. **The Iron Blow Area, Pine Creek Dist.** J. M. RAYNER, P. B. NYE, AND P. S. HOSSFELD. Pp. 12; 3 maps.

No. 15. **Britannia, Zapopan and Mount Wells Areas, Pine Creek Dist.** J. M. RAYNER, P. B. NYE, AND V. M. COTTLE. Pp. 9; 3 maps.

No. 16. **Geophysical Report on the Hercules Gold Mine, Pine Creek Dist.** J. M. RAYNER AND P. B. NYE. Pp. 4; 1 map.

No. 21. **Quartz Body at Simpson's Gap, Alice Springs.** P. S. HOSSFELD. Pp. 2; 1 map.

No. 23. (Sup. to No. 4) **Second Report on Magnetic Prospecting at Tennant Creek (1936).** L. A. RICHARDSON, J. M. RAYNER, AND P. B. NYE. Pp. 9; 8 maps.

No. 26. **The Evelyn Silver-Lead Mine, Pine Creek Dist.** P. S. HOSSFELD, J. M. RAYNER, AND P. B. NYE. Pp. 4; 1 map.

No. 27. **The Maude Creek Mining Centre, Pine Creek Dist.** V. M. COTTLE. Pp. 4; 1 map.

No. 29. **The Home of Bullion Mine, Central Australia.** P. S. HOSSFELD. Pp. 9; 1 map.

No. 30. **Preliminary Report on the Granites Gold-Field, Central Australia.** P. S. HOSSFELD. Pp. 5; 1 map.

No. 32. (Sup. to No. 19) **The Wallaby Silver-Lead Lode, Daly River Dist.** P. S. HOSSFELD. Pp. 2; 1 map.

New Jersey Geodetic Control Survey Bench Marks in Camden, Gloucester and Salem Counties. N. J. Dept. Conserv. and Devel., Geol. Ser. Bull. 51. Trenton, 1940. *Elevations and descriptions of 889 bench marks.*

SOCIETY OF ECONOMIC GEOLOGISTS

ANNUAL MEETING.

The Society of Economic Geologists will meet with the American Institute of Mining and Metallurgical Engineers in New York City on February 17 to 20, 1941. Joint sessions with the Mining Geology Committee and possibly with the Industrial Minerals Division of the Institute will be arranged. The Program Committee of the Society of Economic Geologists has announced a group of papers on strategic minerals, arranged by John M. Boutwell. Although papers on this subject are especially solicited, it is hoped that other phases of economic geology will be represented on the program.

The annual dinner of the Society will be held on Tuesday, February 18, and following the dinner, G. F. Loughlin will give his presidential address.

Abstracts of all papers to be presented before the Society should be in the hands of the Chairman of the Program Committee (Professor Quentin D. Singewald, Department of Geology, University of Rochester, Rochester, New York) by December 1 in order to have a place on the official program. Abstracts should be submitted in duplicate on blanks which will be furnished by the Chairman of the Program Committee or by the Secretary on request. Abstracts will be printed in the January-February number of Economic Geology, which will reach members residing in North America in advance of the meeting.

If you plan to give a paper, please communicate with Professor Quentin D. Singewald as soon as possible.

W. D. JOHNSTON, JR.,
Secretary.

SCIENTIFIC NOTES AND NEWS

G. M. SCHWARTZ has been granted a leave of absence from the University of Minnesota for the academic year 1940–41. He will act as visiting professor in economic geology at the School of Mines recently established by the Faculty of Science of the Université Laval in Quebec. D. M. DAVIDSON has been appointed to lecture in economic and engineering geology at the University of Minnesota during the absence of Dr. Schwartz.

R. S. MOEHLMAN has moved his office from Inspiration, Arizona to 600 Gordon Ave., Reno, Nevada.

D. F. MACDONALD, professor of geology at St. Francis Xavier University, Antigonish, N. S., has been reengaged as geologist with the Panama Canal Commission.

STEWART CAMPBELL, formerly Inspector of Mines in Idaho, is now general manager of the Queen mine at Bellevue, Idaho.

The Appalachian Geological Society sponsored a field trip at Niagra Gorge and vicinity on October 4th and 5th to study the outcrops of horizons which have deep oil producing possibilities in the Appalachian area. C. A. HARTNAGLE was in charge. A dinner on October 4th was addressed by L. C. SNYDER, president of the American Association of Petroleum Geologists and R. E. SHERRIL of the University of Pittsburgh.

E. F. FOX has been promoted from assistant to associate professor of geology at the University of Alaska.

J. B. TYRRELL, president of the Kirkland Lake Gold Mine Co., received an honorary degree at the fall convocation of Queens University.

W. L. RUSSELL is geologist for the Well Surveys, Inc. in Tulsa, Oklahoma.

WILLIAM AGAR spent the summer field season in geological work in Connecticut and is now teaching two days a week at Columbia University.

T. A. RICKARD has commenced the writing of a history of Canadian mining.

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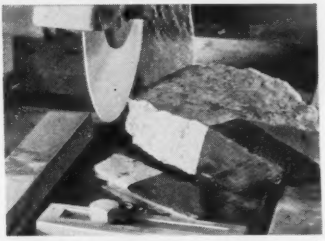

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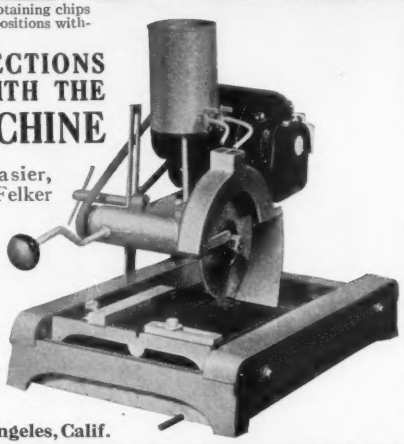

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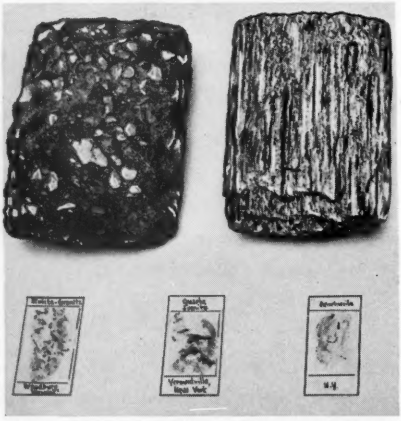

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Rosenbusch, H., Mikroskopische Physiographie der Petrog. Wichtigen Mineralien, 5th Ed. 1st Hälfte by E. Wülfing, 1924; 2nd Hfte. by O. Müggee, 1927. 2 vols. ($48.50.) Buckram	25.00

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